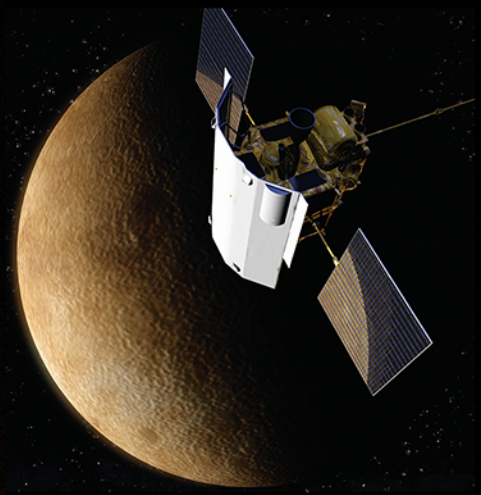
Aerospace Project Management Handbook







M. Ann Garrison Darrin and Patrick A. Stadter

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Aerospace Project Management Handbook


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Edited by
M. Ann Garrison Darrin
Patrick A. Stadter



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Preface

Aerospace project management with an emphasis in space systems is a discipline unto itself. Aerospace project management encompasses intricacies not seen in many terrestrial activities. These range from additional compliance requirements from earned value management and regulations (such as ESA, NASA, FAA, etc.) to criticality and risk factors for systems where traditional repair is impossible and innovative, cutting-edge technology is deployed. As the space industry has matured, the role of project management has evolved to be a discipline-proven approach to success in the unique and unforgiving space environment. In a handbook style, this book offers step-by-step approaches with an emphasis on applied techniques and tools. The handbook is designed to be the foundation work for seasoned program managers, new project managers, technical leads, systems engineers, and principal payload leads.

Although many of the examples in this book are derived from space programs supporting NASA, and the U.S. Department of Defense, the same discipline applies to commercial programs. The corporate knowledge contained in this book has one purpose: to reduce risk in spacecraft missions and to achieve success.


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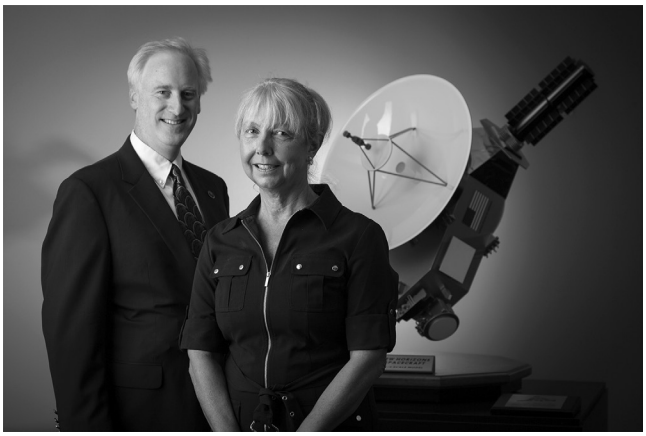
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Of course, our gratitude goes to our respective spouses, Armond Darrin and Carmella Stadter, and children young and old. Appreciation to Melanie Revells (JHUAPL intern 2016), who gathered Appendix A input. Always a delight to work with Taylor & Francis/CRC Press and editor Jonathan Plant.


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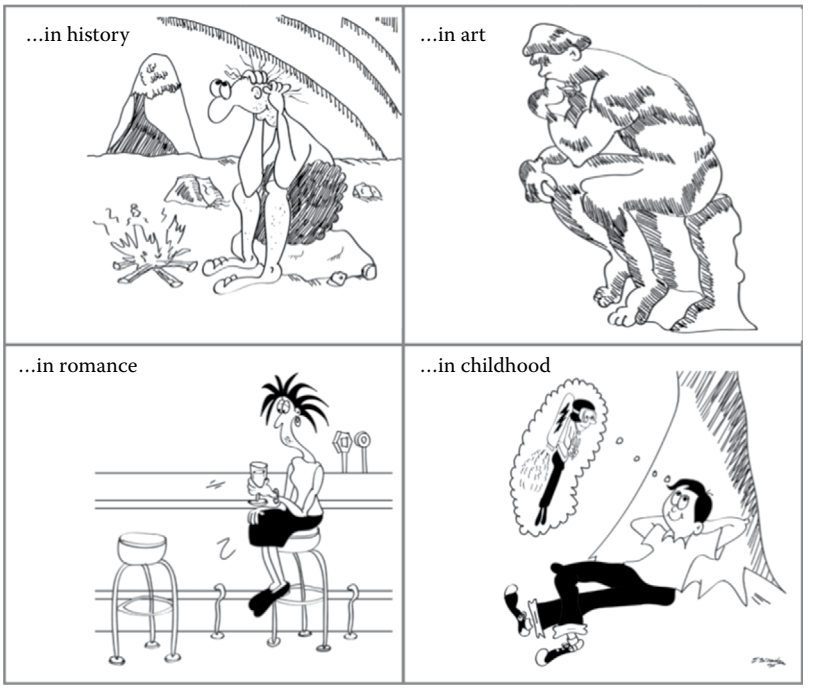
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Section I

Aerospace Project Development Topics

Project Management—Pre-Phase A (Conceptual Study)




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Planning for Project Success

Helmut Seifert

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PROGRAM MANAGEMENT – ONE OF THE OLDEST PROFESSIONS IN THE WORLD

Introduction

What better place to start this handbook on managing aerospace projects than to ask ourselves what a project is. A good working definition as provided by the Project Management Institute (PMI) *A Guide to Project Management Body of Knowledge* (PMBOK) [1] is that a project is a *temporary* undertaking (i.e., with a definite beginning and end) to create a *unique* product, service, or result (see Section 1.2 of the PMBOK). By these criteria, project work is different from operational work (examples are accounting and product manufacturing), which is typically *repetitive* (following existing organizational processes) and produces more or less the *same* product or result repeatedly. The end of a project is reached when either (1) its objectives have been achieved, (2) the project is terminated because its objectives will not or cannot be met, (3) the need for the project no longer exists, or (4) the client or customer wishes to terminate the project.

Projects are progressively elaborated through continual and constant modification, improvement, and detail as new information becomes available. They often consist of many interrelated activities and may be performed not only by various parts of the organization but frequently with other agencies (partners, vendors, subcontractors). Because of these factors, and the resulting necessary level of coordination, projects require active project management.

Aerospace and, in particular, space projects differ from other types of projects (such as consumer product development) in that they are generally very complex, with many "moving parts," are generally very costly (see Figure 1.1), and have a very broad group of stakeholders (including the public). Such projects have therefore very high visibility—especially when things go wrong or there are significant cost overruns (good examples are the Mars Climate Orbiter, the Hubble space telescope, and the International Space Station). Aerospace projects also have very low tolerance for risk since very expensive hardware and/or human life are at stake (good examples are the initial SpaceX Falcon 9 and Orbital ATK Antares commercial launch failures, Apollo 1, and Space Shuttles Challenger and Columbia). Finally, space projects are technologically challenging since the hardware has to withstand the stresses of launch and must operate reliably in harsh environments (such as very low or very high temperatures and high radiation) and at the same time are expected to be of low power, mass, and size.

The following sections focus first on why project planning is so important and then elaborate on some of the key elements, including (1) identifying and capturing project goals, objectives, and scope; (2) identifying and managing communication with stakeholders; (3) staffing a competent project team; (4) constructing a realistic project schedule and budget; and (5) planning for risk management. Finally, this chapter concludes with a brief overview of other important planning activities, including planning for how to adequately address quality requirements and planning for supplier involvement in the project.

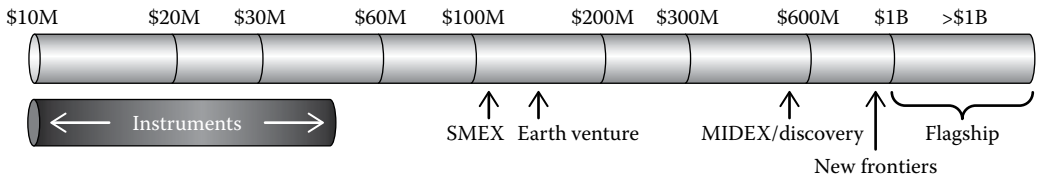


FIGURE 1.1
Cost of NASA space projects.

Importance of Good Project Planning

"If you fail to plan you are planning to fail…" (Anonymous)
"… We don't know where we're going, but we're getting there really fast!" (Anonymous)

Project planning is one of the most critical activities in project management and yet is frequently either performed only perfunctorily or not at all. Project planning often, and of course erroneously, is considered a one-time activity that is carried out exclusively by the Project Manager and only in the early stages of a project. In reality, to be useful, planning needs to be an *ongoing* effort in which, apart from the Project Manager, many of the other stakeholders and team members must participate. Some of the most significant contributions to the project plan, particularly related to the scope, schedule, and quality, come from the project engineering team and, in particular, from the lead systems engineer.

Lack of planning can have many undesirable consequences, including cost/schedule overruns, failures during inspection and testing, and rework. Inadequate planning may even cause problems for the customer after delivery. Also, since the project team may be constantly "putting out fires," the work environment can become demoralizing and stressful, which inevitably will lead to further problems. In summary, for projects to be successful, it is imperative to stay ahead of developments on the ground at all times not only by continually anticipating problems, formulating mitigations and fallback plans, but also by positioning the project to exploit opportunities as they arise.

There are some standards, guidelines, and best practices that address project planning. The best known, which are summarized in Table 1.1, are the PMBOK, the Software Engineering Institute (SEI) Capability Maturity Model® Integration for Development (CMMI®-DEV) [2], and the SAE Aerospace AS9100C standard [3]. It is very useful to be familiar with these and to appropriately leverage elements of each as required (for instance, contractually). The resulting project plan that formally documents all the outputs of the planning effort can either be a stand-alone, single document or a collection of documents that address the various planning areas (for more details, see, e.g., Appendix H of the NASA Space Flight Program and Project Management Requirements [4]).

Understanding the Goals, Objectives, and Scope of the Project

It is impossible to plan and execute a project or to track project progress, unless the goals, objectives, and scope of the project are thoroughly and completely understood. It is also important to determine the project's and product's lifecycle phases to establish well-structured and agreed-upon periods of activities that guide project planning, implementation, evaluation, and decision making.

Figure 1.2 shows the traditional project lifecycle breakdown per the PMBOK (for more details, see Section 2.4 of the PMBOK): project initiation, followed by an *iterative* sequence of controlling activities for planning, executing, and monitoring, and finally project closeout. From Figure 1.3 it is apparent that uncertainty, risk, and stakeholder influence, are largest at the beginning of the project, and then decrease gradually until they are negligible toward the end of the project. Also, not unexpectedly, the cost of making changes is smallest at the start

TABLE 1.1

Project Planning according to PMBOK, CMMI-DEV V1.4, and AS9100C

PMBOK	CMMI*	AS9100C
4. Project Integration Management • Develop Project Management Plan 5. Project Scope Management • Plan Scope Management • Collect requirements • Define scope • Create WBS 6. Project Time Management • Plan Schedule Management • Define activities • Sequence activities • Estimate activity resources • Estimate activity durations • Develop schedule 7. Project Cost Management • Plan Cost Management • Estimate costs • Determine budget 8. Project Quality Management • Plan Quality Management 9. Project Human Resources Management • Plan Human Resources Management 10. Project Communications Management • Plan Communications Management 11. Project Risk Management • Plan Risk Management • Identify Risks • Perform Qualitative Risk Analysis • Perform Quantitative Risk Analysis • Plan Risk Responses 12. Project Procurement Management • Plan Procurement Management 13. Project Stakeholder Management • Plan Stakeholder Management	SG 1: Establish estimates • Estimate the scope of the project • Establish estimates of work product and task attributes • Define project lifecycle phases • Estimate effort and cost SG 2: Develop a project plan • Establish the budget and schedule • Identify project risks • Plan Data Management • Plan the Project's Resources • Plan needed knowledge and skills • Plan stakeholder involvement • Establish the project plan SG 3: Obtain commitment to the plan • Review plans that affect the project • Reconcile work and resource levels • Obtain plan commitment	7.1 Planning of product realization • Project Management • Risk Management • Configuration Management • Control of Work Transfers 7.2 Customer-related processes • Determination of requirements related to the product • Review of requirements related to the product • Customer communication 7.4 Purchasing • Purchasing process • Purchasing information • Verification of purchased product

* "Project Planning" (PP) in CMMI is complemented by specific goals and practices from other process areas such as "Requirements Management" (REQM), "Requirements Development" (RD), "Risk Management" (RSKM), and "Supplier Agreement Management" (SAM), and "Configuration Management" (CM).

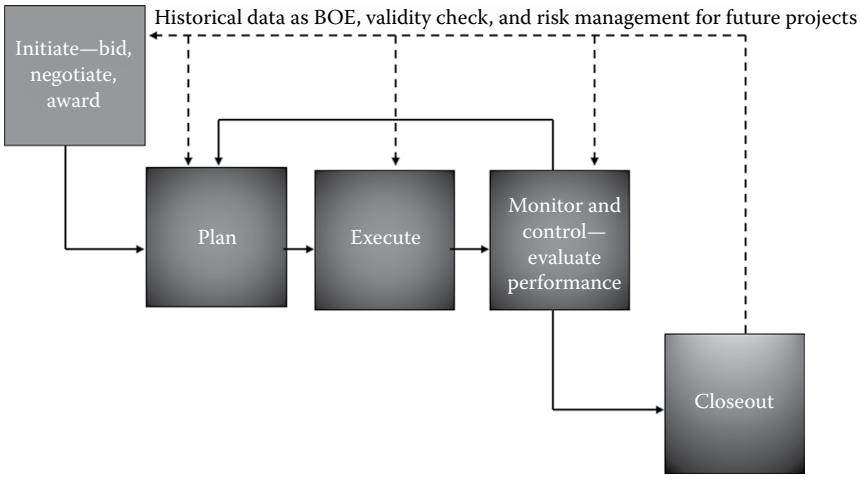


FIGURE 1.2
Project lifecycle (per the PMBOK).

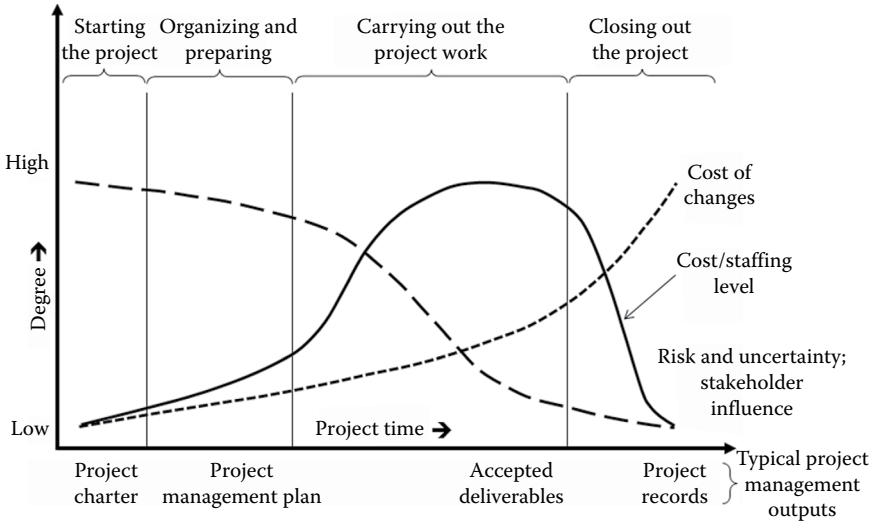


FIGURE 1.3
Stakeholder influence, risk/uncertainty, cost of changes, and cost/staffing levels over the project lifecycle. (Adapted from PMBOK, Figures 2-8 and 2-9.)

of the project and then exponentially increases as the project matures. Finally, cost and staffing levels are highest while the project work is carried out and less so during initial planning and near closeout.

The project lifecycle can encompass the entire engineering/product lifecycle for smaller projects (see Figure 1.4) but, more likely, for large aerospace projects, *repeats* for each phase of the engineering/product lifecycle as shown in Figure 1.5. NASA space projects all follow the engineering/product lifecycle shown in Figure 1.6 (Adapted from the *NASA Systems Engineering Handbook* [5]). Each of these lifecycle phases is separated from the next by a Key

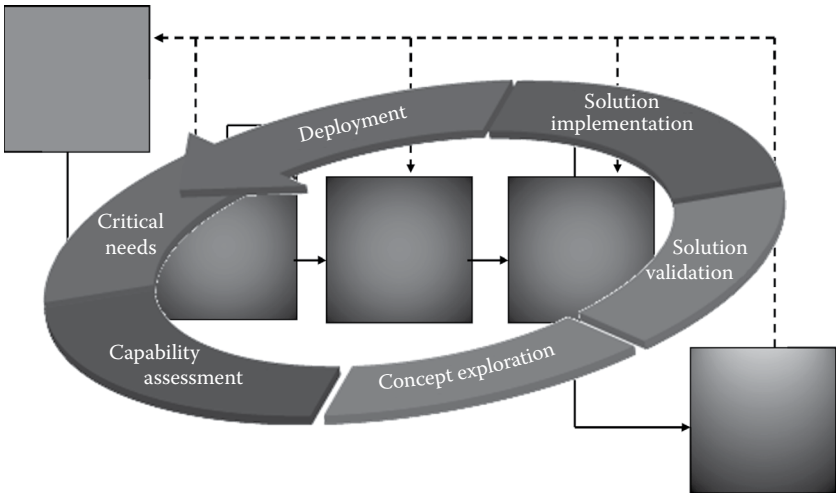


FIGURE 1.4
Product/engineering lifecycle and project lifecycles for small, simple projects.

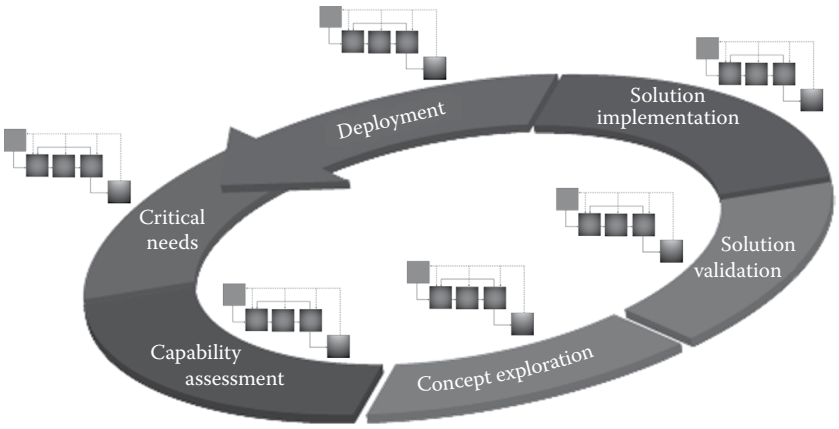


FIGURE 1.5
Product/engineering lifecycle and project lifecycles for large, complex projects.

Formulation			Implementation			
Pre-Phase A: Concept studies	Phase A: Concept and technology development	Phase B: Preliminary design and technology completion	Phase C: Final design and fabrication	Phase D: System assembly, integration and test, launch	Phase E: Operations and sustainment	Phase F: Closeout
Feasible concept →	Top-level architecture →	Functional baseline →	Allocated baseline → Product baseline	▶ As-deployed baseline		
Major reviews ▼	▼▼▼	▼	▼ ▼	▼▼▼▼	▼ ▼ ▼	▼
KDPs ▲	▲	▲	▲	▲	▲	

FIGURE 1.6
NASA project lifecycle. (Adapted from *NASA System Engineering Handbook*, Figure 2.2-1, page 6.)

Decision Point (KDP) and typically constitutes an entire PMBOK project management lifecycle for the performing organization(s).

It is essential for the project team to identify (1) all project requirements (in this process, it is important to remember that requirements are not always explicitly stated but may be included by reference, or may be implicit and need to be inferred or derived); (2) all the deliverables and associated project acceptance criteria/critical success factors; (3) project boundaries (i.e., explicit *inclusions* or *exclusions* from the scope); (4) external interfaces; and (5) all project assumptions and constraints.

One of the most critical inputs to this process is the Statement of Work (SOW), which captures (in more or less detail) all the customer's expectations regarding project deliverables, as well as other considerations such as contractual or regulatory requirements (e.g., warranties, penalties, incentives, export control, regulations, nondisclosure agreements) that are essential to the planning process.

There are many techniques to effectively identify, collect, and develop project technical and performance requirements (e.g., see Section 5 of the PMBOK [6] or the CMMI-DEV chapter on "Requirements Development" [7]). Most of them involve careful problem analysis, context/use-case development, and document review by (teams of) subject matter experts, discussions among the customer, project team, and subject matter experts, and often even proof-of-concept prototyping. The output of the requirements identification and development process should be a stakeholder agreed-upon set of programmatic, technical, and performance requirements and related deliverables that define the scope of the project, which then needs to be planned, executed, and tracked.

A standard and effective way of structuring the entire project within the identified scope is using a work breakdown structure (WBS), which is a product ("deliverable") oriented hierarchical breakdown of all project-related goods and services that divides the effort into tasks ("actual work"). Tasks should be manageable, measurable, and "integrate-able."

An aerospace project WBS is always a mixture of product and programmatic work packages and should be constructed according to the "100% Rule," that is, 100% of the work required by the project scope and all the deliverables must be captured.

The WBS is *the* single most important management tool—not only for describing the entire project as a summation of subdivided elements—but it is also the tool that provides a common framework for virtually all project management tasks, particularly planning. Apart from schedule construction, establishing costs and budgets, and assigning staff and responsibilities for each element, during project execution the WBS is used for project tracking and status reporting. Following Section 1.6, Technical Planning, of the NASA Systems Engineering Handbook, WBS construction (see Figure 1.7) typically starts with the product breakdown structure (PBS), supplied by engineering (led by the Lead Systems Engineer), with the specified primary product and service at the top and all systems, segments, subsystems, etc., and support related efforts at successively lower levels. The WBS is then built from the PBS by adding to each element (including at the system level) any required service or level-of-effort elements (management, systems engineering, Integration and Verification [I&V], integrated logistics support, and so on).

Engineering inputs are indispensable in this process to ensure accuracy and realism. Project WBSs should be carried down to the level appropriate to the costs and risks to be managed. Hence, the proper level of detail for a "cost account" is determined by management's desire to have visibility into costs and should be balanced against the *cost and complexity* of the planning and reporting efforts.

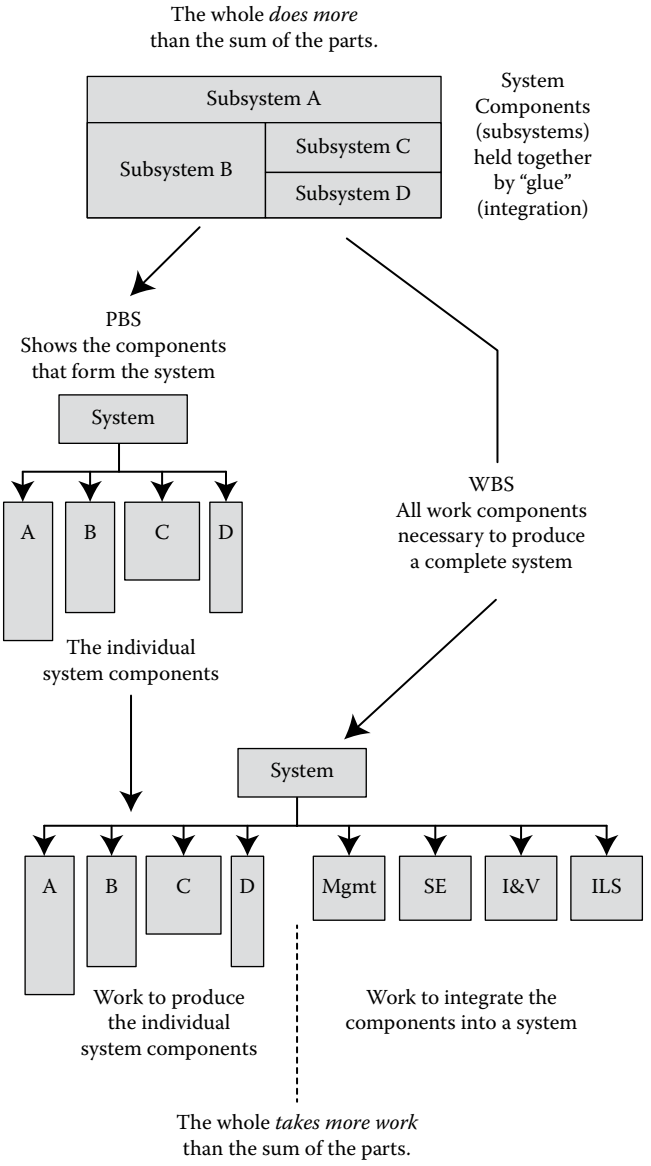


FIGURE 1.7
WBS construction. (Adapted from *NASA Systems Engineering Handbook*, Figure 6.1-4, page 123.)

Identifying and Effectively Engaging and Communicating with the Project's Stakeholders

Identification and effective engagement of all project stakeholders and managing their expectations are crucial for project success and dramatically increases the likelihood of smooth acceptance of project deliverables. Another benefit is that concerns can often be addressed long before they develop into issues or risks. It is, therefore, important to identify

all relevant stakeholders and their respective influences and levels of interest as *early* in the project as possible. As the context diagram in Figure 1.8 shows, both internal and external project stakeholders need to be considered. The project team needs to ensure that in particular the *key stakeholders* (the "Promoters" in the upper right/left quadrant of the influence/interest chart of Figure 1.9), who both have significant impact on and interest in the project, are actively engaged on a regular basis noting that the exact list of these stakeholders will likely evolve over the project lifecycle. Truly effective stakeholder engagement must happen at *all levels*, that is, not only at the management but also at the technical level. The Lead Systems Engineer, in particular, can play a key role in this context since he/she may interact with customers and suppliers as well as the internal engineering team. The project should identify the roles, responsibilities, and expertise of all the relevant stakeholders on the project

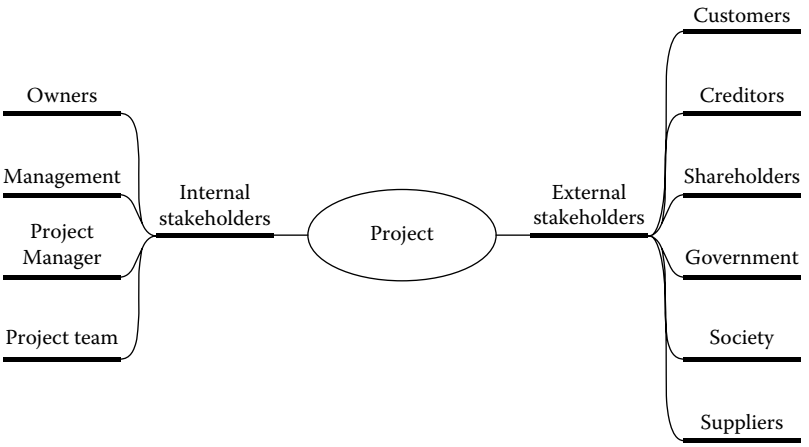


FIGURE 1.8
Project stakeholders.

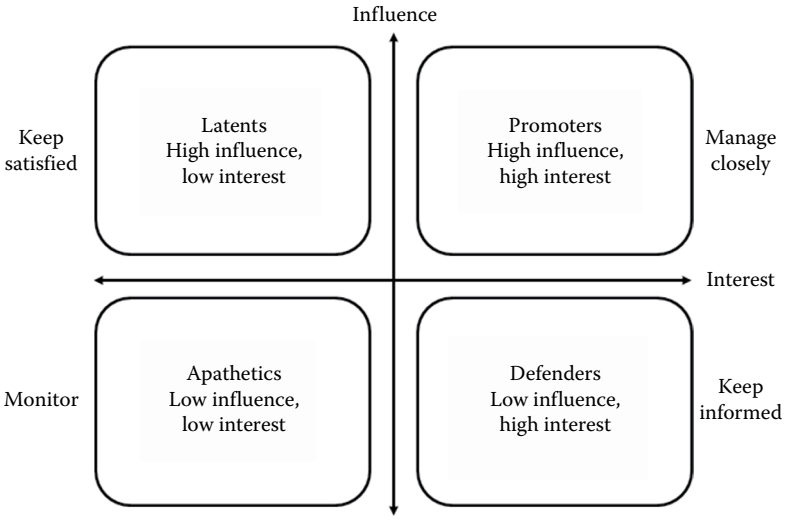


FIGURE 1.9
Stakeholder influence and interest.

Stakeholders	Communication Type	Objective of Communication	Medium	Frequency	Owner	Deliverables
Customer project team management	Kickoff meeting	Introduce the project team and project. Review project objective and mangement approach	Face to face	Once	Project Manager	Agenda meeting minutes
Project team	Project team meetings	Review status of the project and discuss issues with the team	Face to face conference call	As needed	Project Manager	Agenda meeting minutes
Customer project team management	Monthly project status reports	Report the status of the project incl. activities, progress, issuess, cost, schedule	Email	Month	Project Manager	Project status report
…	…	…	…	…	…	…

FIGURE 1.10
Sample stakeholder communications plan.

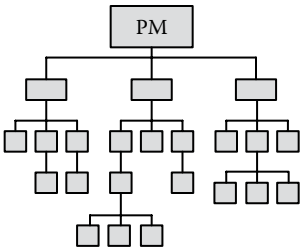
and develop targeted communications strategies for each, including communication form, timing/frequency, and level of detail. Figure 1.10 provides an example for a simple stakeholder communications plan (for more details, see Sections 2.2 and 10 of the PMBOK).

Putting Together the Project Team

Having access to the right people, with the right skills mix, can make or break a project. Early in the project, the project leadership (Project Manager and Lead Systems Engineer) should identify all the capabilities, knowledge, and skills that will be needed for project success and also think about related "gaps" within the organization that may require external support from partners, vendors, or subcontractors. How to plan for your project team critically depends on the organizational culture and structure (functional, matrix, or "projectized") within which the work is to be performed since the Project Manager's relative power and access to (and control of) project human resources will vary widely depending on organizational culture and structure (for more details, see Sections 2.1 and 2.3 of the PMBOK).

In "projectized" organizations there will generally not be a "pool" of qualified "readily available" staff to draw from as compared to a matrix organization, which may have functional groups of staff with the needed, specialized knowledge. Project staff in these types of organizations typically are collocated, report only to the PM (not to a functional manager), and form strong loyalties to the project, not to a functional manager. Disadvantages include resource utilization inefficiencies (e.g., occasional need only for specialized skills) and that, as the project ends, team members may be out of work. Therefore, the Project Manager, being responsible for staffing the project with the required skill set, will need to acquire all the necessary human resources by hiring or outsourcing.

In matrix or functional organizations, on the other hand, the required project resources will generally need to be negotiated between the Project Manager and "line management"



Hierarchical-type organization chart

Role \ WBS	100 Plan Product	200 Develop Product	300 Release Product
Project Manager	R	A	I
Lead engineer	A	I	A
Configuration manager	I	I	R
Developer	C	R	I

FIGURE 1.11
Useful tools for documenting project roles and responsibilities.

and, in the case of competition for certain resources, priorities will need to be deconflicted. Apart from competition for resources, another disadvantage of these types of organizations is inefficiencies caused by the dual-reporting structure for staff and the Project Manager's lesser authority.

Identifying the right people with the right skills for the project can only be done once the goals, objectives, requirements, scope, and lifecycle of the project have been determined. The actual availability (or nonavailability) of resources *inside* the organization can not only drive the project schedule and cost, but also partnering and supplier decisions by the project management.

Figure 1.11 shows two of the most important tools that are typically used for staff project planning, and to document project roles and responsibilities: the Organization Chart and the Responsibility Assignment Matrix (RAM), which is also often called the "RACI" (Responsible, Accountable, Consult, Inform) chart. These tools are agnostic regarding whether the project staff is from inside the organization or from the partner or supplier organizations (for more details, see Section 9 of the PMBOK).

Determining Project Schedule and Project Cost

Products in the project WBS are the result of activities that take time to complete. These activities have time-precedence relationships among them that can be used to construct a *network schedule* that defines the dependencies among activities, available resources, and external receivables. A network schedule is a standard method to define and communicate what needs to be done, how long it will take, and how each element in the WBS affects other elements. In particular, it supports quantitatively answering important questions such as how long it will take to complete a project, which activities drive that duration ("critical path" activities), and how much spare time ("float") exists for all the other project activities.

To arrive at a project schedule, the Project Manager and engineering team initially define all the activities to complete each WBS "work package" and then sequence the activities, for example, using a network diagram. The next step involves identifying all the required *resources* for each activity (i.e., people, equipment, materials/supplies), and then to estimate the *duration* of each activity (i.e., the work periods required to complete the activities with the identified resources), before developing from these the final schedule (which can be either in network or "Gantt" format).

There are several tools and techniques that are typically used for estimating activity durations (for more details, see Section 6 of the PMBOK) and, when combined with resource estimates (in some organizations this is called "loading the schedule"), activity costs: most common are the "expert judgment" and analogous or "top down" estimating methods. Both are estimates by experienced staff (often staff that will perform the activity), with the exception that the latter also is based on actuals for a similar activity completed on a previous project). "Three-Point" (i.e., most likely, optimistic, and pessimistic) estimates are also typically provided by experienced staff and are averaged for a final estimate. "Three-Point" estimates are also important for schedule robustness analysis, such as Program Evaluation and Review Technique (PERT) or schedule/cost reserve adequacy analysis such as the Joint Cost and Schedule Confidence Level (JCL).

Engineering estimates, also often called "grassroots" or "bottom-up" estimates, are the result of rolling up all the costs estimated by each organization performing the work described in the WBS. Some of the disadvantages of this method are that it is typically very time-consuming and labor intensive and also that each time a "what if" question is raised or assumptions change, a new estimate needs to be made (for more details, see Section 7 of the PMBOK and Section 6.1 of the NASA Systems Engineering Handbook).

Another popular method is "parametric estimating," which involves collecting and aggregating relevant historical data at an appropriate level of detail and then applying them to the project item to be estimated by constructing suitable "cost-estimating relationships" (CERs).

Once the final project schedule and project cost have been created, various important analysis tasks can be performed. The most common, and necessary for project success, are reserve analysis both for known project risks and liens and assessing unknown unknowns. The former requires allocating resources as appropriate funded schedule reserves and the latter requires allocating adequate management or cost reserves Other frequent tasks involve the mentioned schedule network analyses, such as PERT, "critical path" analysis, and what-if-scenario analyses, for example, using Monte-Carlo techniques. Schedule compression techniques commonly used for replanning to make up for schedule delays include "crashing," which however *increases resources and cost*, and "fast tracking," where the team identifies tasks that can be performed *in parallel*. When resources are limited or overallocated, the Project Manager may use "resource leveling" or the "critical chain" method (basically a "resource-constrained critical path") to reconcile the resource availability and schedule.

Schedule and cost are two of the *key* project metrics that will be used during project execution to status and correct (as necessary) project progress. For example, Earned Value Management (EVM), which critically relies on the project baseline integrated schedule and budget, is one of *the* most important management tools for measuring how much work has been completed for the money spent and comparing these metrics against the nominal plan. Because of this, cost and schedule need to be continually reviewed and updated as necessary to accurately and realistically reflect the project plan.

Developing an Effective Project Risk Management Program

Risk management *is* project management and should be embraced by the Project Manager and team as part of the "project culture." Risk management is like playing chess—good players see many moves in advance and make current moves

accordingly! To get the maximum benefit, it needs to be a continuous, proactive process to identify, assess, and manage the project risks and opportunities to minimize the impact of risks and maximize the benefits of opportunities on your project. When done correctly and consistently, risk management is a great communication tool within the project team, as well as with customers, senior management, and partners or suppliers (for more details, see Section 11 of the PMBOK and Section 6.4 of the NASA Systems Engineering Handbook).

A recent (2012) successful project managed by the Johns Hopkins University Applied Physics Laboratory (JHU/APL), the Van Allen Probes (VAP), can serve as an example. Because of a comprehensive, ongoing, proactive risk management program, major risks (in particular, significant schedule delays and cost impacts) could be averted or accepted and corrected under favorable conditions. The project team, the NASA sponsor (NASA/Goddard Space Flight Center and Headquarters), and JHU/APL Senior Management were well informed about the project risks at all times. The VAP risk management system, therefore, was viewed as a great success by the customer and the project team received compliments throughout the development cycle. Active risk management also assisted in successfully and smoothly completing milestone reviews and KDP reviews since the Standing Review Board (SRB) and Independent Program Assessment Office (IPAO) personnel could be quickly brought up to speed and agreements reached regarding the risk project posture and mitigation plans.

When planning for risk management, or how to proceed with specific risks, one should consider not only that the approach is sensitive to stakeholder (in particular, customer) expectations and requirements, but also that appropriate thresholds are agreed upon. Commodities or low-impact issues should not be treated the same way as technically complex, and/or potentially high-impact issues and, therefore, a "graded" versus a "one size fits all" approach to risk is appropriate. NASA for this reason has adopted its A through D Risk Classes for all missions. Risk Class A missions (e.g., manned missions, Hubble Space Telescope, Cassini, James Webb Space Telescope) are the most critical for the Agency Strategic Plan; are of very high national significance, complexity, and cost; have long mission lifetimes; and, therefore, involve the most comprehensive and rigorous set of risk management and assurance practices. Risk Class D missions (e.g., technology demonstrations, Small Explorers [SMEX]), on the other hand, generally have low priority; are of medium to low national significance, complexity, and cost; have short mission lifetimes; and, therefore, the project team may determine that it is acceptable to employ significantly less comprehensive and rigorous practices [8]. Risk decisions should always be based on criteria that are carefully structured and are meaningful for the particular project at hand (e.g., criticality to the national interest, loss of life or high-value equipment, safety of humans, animals, or the environment).

The typical risk management process involves steps such as risk identification, risk classification, risk analysis, risk response planning, risk monitoring, and risk control. There also is an important communications aspect to risk management that needs to be planned and performed.

As part of risk identification, the project team considers various scenarios that could impact mission safety or success. For this, typically, mission requirements and the Concept of Operations are reviewed for technical performance risks. It also is very useful to review existing risk or lessons learned databases for relevant risks from similar programs. Finally, risks to meeting programmatic commitments (e.g., schedule, cost) are considered as well.

Risk categorization involves evaluating the timeframe of the risk (i.e., short-term or long-term risk) and then whether the risk is of a technical, quality, safety, or performance nature, or rather a programmatic/organizational risk (cost, schedule, scope; staffing, equipment/facilities, financial). Finally, it is also useful to explicitly identify external risks such as risks with the supply chain, the customer, or regulatory/government concerns.

As part of risk analysis, the team estimates both the likelihood of occurrence and also the consequence (or impact) of each risk. The PMBOK considers both qualitative and quantitative approaches (see Sections 11.3 and 11.4) to assessing the effect of identified risks on overall project goals and objectives. The project engineering team may use Failure Mode Effect Analysis (FMEA), Probabilistic Risk Assessment (PRA), and other technical risk analysis techniques as appropriate. Lastly, after the analysis has been completed, risks are classified and prioritized according to their likelihood (L) and consequence (C), for example, using a 5 × 5 matrix, as well as according to their severity (usually defined as "L × C" or "L + C"), that is, "high" (red), "medium" (yellow), or "low" (green) severity, shown in Figure 1.12 in dark, light, and medium gray shading, respectively.

During risk planning, the project team or, more often, a dedicated risk board determines and implements a plan of action for each risk (i.e., accept, mitigate, watch, research, elevate, close) and assigns each risk to a team member (the "risk owner") responsible for the management of the risk item. At a minimum, risk mitigation plans and/or contingency plans should be developed for all "red" and "yellow" risks. The risk board also updates the risk database and makes risk information available to the program team and other stakeholders.

As part of risk monitoring, the project team watches for risk indicators such as changes in previously identified risks and also for new or emerging risks. Each risk owner should acquire, compile, and report data on the risk status and effectiveness of the risk mitigation plan of action. As part of risk control, the risk board makes decisions based on the current risk severity, the effectiveness of the action plan, and the need for further action. Decisions may include continuing as planned, revising the action plan to correct for deviations in the risk and mitigation plan, implementing the contingency plan, accepting the residual risk, or closing the risk.

A common challenge in risk management is the need to distinguish between a project risk and standard, though perhaps challenging, technical activities. Care should be taken during project planning to document what the project considers to be a risk so that the risk

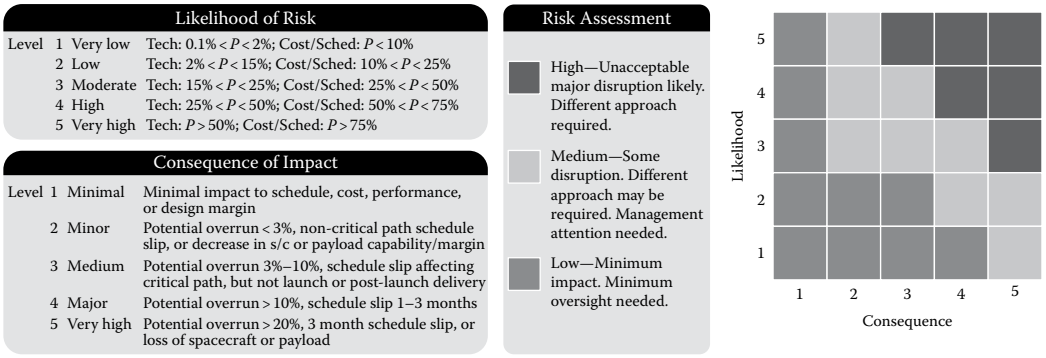


FIGURE 1.12
Risk categorization and prioritization.

management process does not become overly burdensome on the project team. A typical rule of thumb is that a risk is an issue that requires extraordinary measures to be taken to mitigate it.

Other Planning Activities for Successful Projects

Other planning activities important for project success deal with planning the project's quality management and procurement management approaches. These activities, as was the case for the others discussed in the earlier sections, also involve stakeholders beyond the Project Manager, such as engineering and the organization's quality, purchasing, and contracts functions.

The AS9100 standard places a significant importance on consciously making decisions *early* about the level of quality assurance desired in the product realization process and, ideally, to include members of the quality staff as early as the *proposal development stage*. Doing this helps to identify all the customer's quality requirements (explicit *and* implied) and to verify that all requirements in the solicitation are addressed. It also helps to establish the appropriate quality level for the proposed technical tasks, to identify and explain the implications of quality decisions, to assist with the selection of suppliers, and to ensure information about a potential supplier's quality activities is accurate. Finally, due to the size and complexity of many aerospace missions today, multiorganization *partnership arrangements* are often developed rather than just simple buyer/supplier relationships. It is essential to achieve early agreement (again, ideally during the proposal phase) on how the primary organizations' mission assurance programs can coexist without forcing one or the other partner to change their ways significantly.

AS9100's rationale for making quality decisions a part of the proposal process is that historically the focus is *only* on engineering, management, and finances. However, when organizations forget to include quality in this process, the repercussions during the *execution* of the task can be significant. Also, during the proposal phase, quality staff can translate "quality-ease" into the organization's language so that the engineering team can more easily understand requirements, and alert the project team when requirements may commit to levels of quality (workmanship, cleanliness, certification, record control, supplier management, etc.) that the organization either is incapable of meeting or philosophically may disagree with. Finally, sometimes customers may be unaware of certain unintended and possibly costly requirements in their contract language that the performing organization's quality staff may be able to identify and, hence, can be renegotiated and perhaps eliminated.

Quality planning always involves a cost-benefit analysis and a thorough assessment of the various aspects of cost of quality (e.g., see Section 8.1 of the PMBOK), that is, the cost of conformance (prevention and appraisal costs) and cost of nonconformance (internal or external failure costs), and perhaps even a benchmarking activity against comparable other (current or previous) projects. When doing this trade, it is important to remember the "1-10-100" Rule, developed by George Labovitz and Yu Sang Chang in 1987 [9], which roughly states that each one dollar spent on prevention will save $10 on correction and $100 on failure costs (field repairs, litigation). For example, BP's Deepwater Horizon drilling rig explosion in 2010, which lead to the largest environmental disaster in U.S. history (incl. 11 human deaths, over $10 billion financial losses for BP, and inestimable environmental loss)

had as one of its root causes weak cement around the well, which was not adequately tested by the contractor in order to save time (9–12 hours) and money (approx. $130 thousand) [10]. The output of these activities and analyses is a quality management plan, which should also contain specific quality metrics that can be used for quality assurance and control, as well as steps for process improvements within the project.

The objectives of procurement planning (e.g., see Section 12.1 of the PMBOK) are to identify and document the procurement approach and decision-making process, perform a make-or-buy analyses, and to perform market research to identify suitable vendors.

During the make-or-buy analysis, the project team determines whether a particular task or component build is best performed in-house or should be procured from an external source. Key considerations in this decision process are both organizational capability, availability of resources, cost, schedule, and risk. Once a decision has been made to outsource a particular portion of work or to purchase certain critical items for the project, the planning process needs to consider the various contract types (i.e., fixed price, cost-reimbursable, time, and material) and determine the best fit, identify a pool of potential suppliers through market research, and develop the criteria that will be used to evaluate and ultimately select suppliers.

These activities culminate in a procurement management plan (which again can be a stand-alone document or a dedicated section of the project plan) and associated documents such as a Supplier Statement of Work; quality, performance, and programmatic requirements to be flowed to candidate suppliers; procurement metrics used for supplier management; and supplier selection criteria and metrics.

Summary and Conclusion

Careful and continual planning of all the project's resources, risks, and activities, and consideration of stakeholder inputs are essential for project success. It helps to anticipate and thereby prevent or mitigate problems down the road at much less cost than would be required later to fix them. Planning also forms the basis for effective project execution, and meaningful tracking and reporting during the implementation phase.

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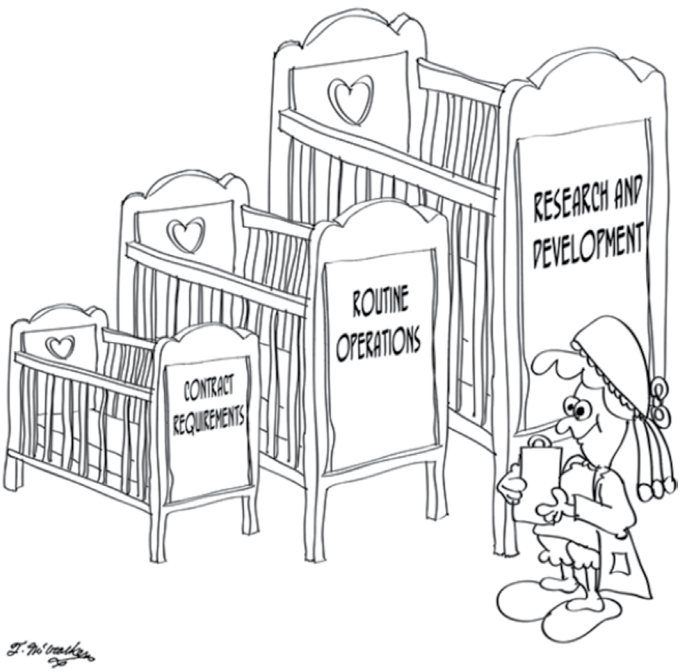
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Finance: Pre-Proposal Activities

Meagan L. Hahn and Jack D. Letzer

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DR. GOLDILOCKS SELECTS THE CORRECT RISK TOLERANCE.

Pre-Proposal Activities: Overview and Introduction

Many months, and even years, in advance of formal federal competitions, such as Broad Agency Announcements (BAA), or other solicitations, teams begin to formulate technical concepts in anticipation of a sponsor's needs, expectations, and requirements. One of the fundamental questions during this early development phase should be "what is the likelihood of delivering this mission, system, or instrument within the expected cost and schedule constraints?" Parametric cost modeling, which relies on top-level technical design parameters as opposed to detailed grass-roots estimating methodologies, enables a relatively quick, yet robust, and data-driven assessment of total mission cost and price risk. The use of technical parameters as primary cost drivers also allows the financial team to be highly integrated with the design team to complete trade studies, thereby optimizing the design for a given cost.

Once mission design requirements have been established, technical leads begin to translate these needs to a point design. The parametric cost analyst should be a key participant in this phase of the design study, as understanding key drivers, significant technical risks, and development efforts are critical to developing a cost estimate that captures the potential range of costs. During conceptual design phases, the requirements and specifications for the concept are in flux. With an integrated parametric cost analysis, the cost estimate can evolve in tandem with the design specifications. Both expected cost and cost risk can be updated to inform the engineering team of the cost effects of their design changes in real time.

Significant cost model inputs include: mass (at the subsystem or component level, depending on design stage and fidelity), technology readiness level (TRL), quantities (flight, spares, prototypes, engineering models [EMs], etc.), precise analogies, sources of heritage (from the component to the mission level), development schedule, power, mission class, and risk posture. Cost models can be anything from commercial "black-box" models to internally developed cost estimating relationships (CERs), to rules of thumb. The primary estimating model should be chosen to balance fidelity, maturity, efficiency, and credibility. Table 2.1 shows how the choice of model complements estimating needs.

A cost estimate is dependent on the quality of its input variables (i.e., garbage in, garbage out). Communication within the project team and attention to details go a long way to avoid errors that can become major mistakes. Some cost models require subjective inputs, such as manufacturing complexity. Practitioners should define and validate cost model inputs with subject matter experts, taking care of document changes and differences of opinion. As an example, if there is uncertainty—or disagreement—in TRL, the modeler has an opportunity to incorporate the cost impact of low TRL (specifically potential nonrecurring engineering (NRE) to advance TRL) into the risk quantification analysis. One can

TABLE 2.1

Cost Model Types and Appropriate Applications

Type of Estimate	Common Parameter(s)	Estimate Detail	Concept Maturity	Estimating Efficiency	Credibility
Analogy	Technical similarity of mission/instrument/etc.	Low	New	High	Low
Rule of thumb	Mass, destination, etc.	Low	New	High	Low
CER	Mass, power, quantity, etc.	Moderate	Ranges	High	Ranges
Commercial model	Detailed mass, power, complexity, TRL, etc.	High	High	Low	Ranges

TABLE 2.2

Technical Readiness Level (TRL) Definitions

TRL Level	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of concept
4	Component/subsystem validation in laboratory environment
5	System/subsystem/component validation in relevant environment
6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)
7	System prototyping demonstration in an operational environment (ground or space)
8	Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space)
9	Actual system "mission proven" through successful mission operations (ground or space)

model the expected value of TRL-6 (new design tested in a relevant environment) while acknowledging and quantifying the cost and technical risk, however slight, of an actual TRL-4/5 (breadboard validation) assessment (see Table 2.2).

Early cost estimates do not add much value to a concept study without an understanding of the associated cost risk. Cost risk quantification entails assessing ranges of estimates that fall within the realm of possibility and assigning a confidence level to a cost estimate based on these ranges, often using Monte Carlo simulations. The confidence level defines the extent to which teams believe their project can be successfully executed at or below the cost estimate. Uncertainty in cost model inputs, such as currently estimated mass versus mass estimates inflated for historical mass growth, TRL, and manufacturing complexity can be used to generate a range of cost estimates to quantify cost uncertainty. As concepts mature, these inputs become better defined, and cost uncertainty diminishes. Quantifying cost uncertainty provides concept study teams with valuable insights about

- Overall feasibility of a concept, given cost constraints
- Range of costs associated with a design solution
- Cost uncertainty drivers, such as low-maturity instruments
- Impact of design trades
- Technical aspects of the concept to focus development efforts during limited proposal preparation time

These insights can help teams focus on the specific areas that provide the greatest improvement to a cost confidence curve.

Along with cost uncertainty associated with parameter ranges and cost model output differences, parametric cost estimators need to quantify cost risk. The project's technical risk list can be used to assess cost risk, assuming the team can assign likelihoods and severities to each of the risks. These inputs are often extremely subjective, and ranges should be used wherever experts provide different opinions.

Risk and uncertainty quantification can be simplified significantly for high-efficiency estimating by using historical cost growth information (e.g., from Preliminary Design Review [PDR] through launch). This information represents the total cost of all types of uncertainties, including parameter uncertainty, cost model output inaccuracy, and realized risks.

Historical cost information is invaluable to the parametric estimator. A database of historical costs, early estimates for implemented projects, schedule growth, recognized risks, mass, and other cost model input parameters from historical projects should be maintained and kept readily available to the cost estimator. These cost ranges are especially valuable during early design phases to articulate cost uncertainty and cost risk to the design team and decision makers.

Why Use Parametric Models?

Relatively Quick Assessment of Cost Feasibility

Parametric models allow estimates to be generated with relatively few technical inputs when time, refined design, and resources are lacking. A preliminary estimate can be generated using a few inputs such as subsystem level mass, power, TRL, and top level heritage/analogies. As stated above, limited technical inputs translate to a higher range of cost uncertainty, but arriving at a potential range of cost is critical to begin assessing cost feasibility during conceptual design phases. The cost and cost risk analysis provide this range of cost with associated confidence levels—*How likely is it for Space Mission X to fit within a given cost constraint*? If the current technical configuration results in a cost-prohibitive estimate, then the Project Manager (PjM) can

- Conduct technical trades to reduce cost and cost risk
- Refine and mature the design to reduce cost uncertainty
- Focus on risk mitigation activities to reduce cost risk

Informing the technical and programmatic team early in the design phase focuses the trade space and prevents expending resources on development efforts for concepts that are not feasible at a given cost and schedule constraint.

Parametric Estimates Are Data Driven

The greatest strength of parametric estimates is in the use of proven, robust, data-driven methodologies. Said processes are geared toward generating estimates that are realistic, given the technical configuration and requirements; in other words, what is the expected value of this subsystem/component/spacecraft/instrument/mission, given historical cost and technical performance of comparable systems? Parametric models and CERs are objective and unbiased, thereby preventing overly optimistic bottom-up estimates (BUE) based on preliminary designs and engineering optimism—this is particularly important for objectively quantifying reasonable costs when the engineering/science team is highly invested in a particular mission or system configuration. As such, parametric modelers, at the conceptual stage, play a critical nonadvocate role on the project. Table 2.3 represents the advantages and disadvantages of BUEs compared to parametric estimates.

The use of bottom-up estimating in early mission design phases was one of the key contributors to major mission cost overruns over the last 20 years before parametric estimates became a requirement for both proposed costs and significant milestone reviews in the aerospace industry. BUEs are more subjective and require specific, detailed inputs that

TABLE 2.3

Advantages and Disadvantages of BUEs Compared to Parametric Estimates

Estimating Technique	Advantages	Disadvantages
Grass-roots estimates (bottom-up)	• Most detailed technique • Best inherent accuracy • Capable of establishing a funding profile • Provides best estimating base for future program change estimates • Commits responsible organization to the stated cost	• Requires detailed program and product definition • Time-consuming • Subject to engineering bias • May underestimate system integration costs • Requires experienced personnel
Parametric estimates (cost modeling)	• Application is simple, quick, and low cost • Statistical database can provide expected values and prediction intervals • Can be used for equipment or systems prior to defining detail design or project planning • Effective for trade studies	• Requires parametric cost relationships to be established • Limited frequently to specific subsystems or functional hardware of systems • Requires extrapolation for new technology or approaches • Depends on quantity and quality of the database • Limited by the available data and the number of independent variables
Comparative estimates (analogy)	• Relatively simple • Low cost • Emphasizes incremental program and product changes • Good accuracy for similarly configured item level	• Requires analogous product and program data • Limited to stable technology • Narrow range of applications • Difficult to extrapolate with confidence • May be limited to systems and equipment built by the same firm

Source: NASA, *NASA Cost Estimating Handbook*, Version 4, NASA, Washington, DC, February 2015.

are not necessarily practical during conceptual/proposal phase. Reasons for this include the fact that the design is not finalized, there are many open technical trades, requirements are uncertain, instrument configurations are not well established, and risks are often poorly understood or not yet identified. Generating a BUE is costly and labor intensive—it requires that specific labor resources, materials, subcontracts, detailed schedules, and other critical cost drivers be identified, factors typically not well understood in a conceptual design environment. The BUE also can be easily manipulated to generate a known, desired cost output just by reducing labor hours, schedule, etc. Both of these elements significantly reduce the extent to which a BUE can be data driven and representative of expected cost.

Conversely, existing parametric models are based on demonstrated statistical relationships between high-level technical parameters and actual costs (e.g., mass, power, TRL). These estimates rely strongly on actual costs from relevant missions/instruments/subsystems. Whenever possible, models can be calibrated to reflect cost and technical performance of a given organization, to prevent homogenization of estimates that don't capture specific organizational efficiencies or technology development efforts. More important, however, is incorporating data-driven cost risk and cost uncertainty in the estimating process. A BUE-only estimate generates a single point estimate with bottom line reserves. It does not show how—or where—costs could grow, nor does it account for uncertainty in the (likely optimistic) point estimate. Parametric models address specific mission cost *risks* (e.g., technology development of a payload sensor that is still TRL-4, aggressive mission schedule, complex composite structure, etc.), along with cost *uncertainty* (preliminary design,

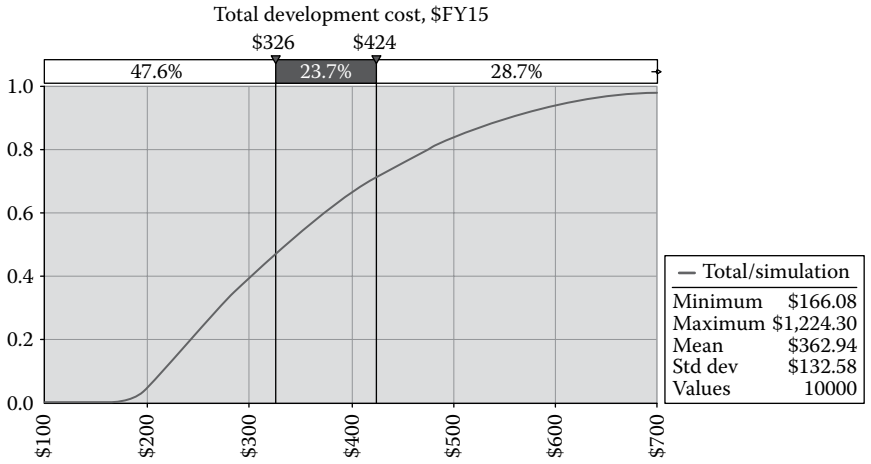


FIGURE 2.1
Cumulative Distribution Function ("S-Curve") for a robotic space mission. This curve demonstrates that the point estimate without reserves falls at the 48th percentile, while the point estimate with reserves falls at the 71st percentile. In other words, there is a 71% chance that the mission will be completed within the proposed cost plus reserves (in this case, 30% reserves). Most customers expect to fund projects at the 70th–80th percentiles to reduce risk of overruns.

uncertainty in the underlying CERs, requirements change, etc.). These ranges can be quantified both with CER model development (statistical ranges), historical cost growth, and discrete cost risks. In short, a robust parametric model incorporates cost, technical, and design uncertainty in a data-driven process. This provides the customer with necessary cost data that is both reliable and transparent with which to make critical funding decisions. An example of a cumulative distribution function of total estimated development cost is shown in Figure 2.1; this shows the potential range of costs with associated probabilities, along with the confidence level of any single point estimate provided by the project.

Estimates Are Mission Specific and Highly Customized

Although a parametric analyst has the capability to run a rough order of magnitude estimate as described above—there is definite value to a quick turnaround estimate in the absence of sufficient technical data—ideally, each estimate is customized to reflect the specific technical requirements of the system in question. Parametric modeling is not a "plug and play" process, as the output (even for quick turnaround cost estimates) must be correctly interpreted and used judiciously. *This is where a broad technical understanding of the system is crucial*; an estimator must be able to look at model output—however detailed—and say "does this estimate make sense given the technology development required, the instrument or spacecraft complexity/simplicity, etc.?" If it doesn't make sense, what are the areas of concern, and what can be done to tailor the estimate accordingly?

This iterative process is the crux of the parametric estimate before the cost risk analysis. Each estimate is unique and takes into account mission-specific requirements, cost drivers, technology development, rebuild, risk posture, etc. At whatever level of detail is appropriate (subsystem, instrument, box-level, component), the analyst relies on accurate cost analogs/modeling methodologies to generate the most credible and defensible estimate, given technical requirements. For example, a new instrument build may plan to reuse electronics from a prior instrument build; in this case, the analyst can use the actual cost data

from the built electronics, quantify the expected savings in NRE, and use that data as a direct cost analogy for the instrument estimate. This data can translate further into the instrument cost risk analysis. The exact cost—without expected savings from NRE—can be used to build the cost risk distribution. This acknowledges and quantifies the risk that a rebuild may not be practical as the design matures and the possible manifestation of this risk (however unlikely) is part of the risk-adjusted cost estimate (e.g., the 70th percentile estimate). Forms of model customization include

- *Direct cost analogy*: Using the actual cost of a highly analogous system (i.e., instrument, subsystem, electronics box, or component). These costs can easily be substituted for cost model output as part of a system level cost estimate.
- *Model calibration*: Many industry-accepted models can be calibrated to an organization's specific cost and technical performance. This allows an estimate to reflect what it costs for ABC contractor to build a Power Distribution Unit (PDU), rather than the generalized cost of industries included in the underlying cost databases. This is especially useful for items with known efficiencies or technology development, as NRE is a significant cost driver for most space systems. For example, if a system requires a new spacecraft processor that is currently TRL-4, the analyst can calibrate the model to a previous new processor development effort. This board may be similar in mass to existing processors, but the cost should still increase significantly—anywhere from 30% to 60%—to cover the NRE to get to TRL-6 by PDR (which is a programmatic requirement for space missions).
- *Model specification*: The parametric analyst is likely to employ multiple hardware models for the same space system, either to target a particular area of concern or as a cross-check to the primary estimate. For example, an instrument estimate may be mainly determined using an instrument-specific cost model, while its data processing unit is modeled separately using a tool that can be calibrated more efficiently to a strong point of heritage/analogous data point.
- *Specific accepted adjustments*: There are many researched, published, and accepted adjustments to cost model output within the space cost estimating community. Similarly to cost model output, these adjustments must be made judiciously and with strong technical justification. Examples of adjustments include instrument TRL, cost-to-copy hardware, software reuse, lower reliability, and mission level cost-to-cost factors for project management oversight costs.

The primary goal of customizing a parametric estimate is to generate a number that is most representative of the expected cost; this just cannot be accomplished in the absence of technical analysis and data-driven processes and adjustments. Accordingly, the parametric analyst is an integrated member of the mission team from the conceptual design phase through the mission's Critical Design Review (CDR), typically the last major milestone before the major hardware building effort. Robust estimates require broad technical knowledge; quantifying and articulating how technical parameters translate to cost is critical to the process. During conceptual design and proposal phases, the analyst works closely with engineers and should be a key participant in technical trades, design-to-cost optimization (optimizing technical performance within a known cost constraint), and strategic risk reduction activities. Through the cost risk analysis, the estimator can determine where dollars should be invested early on to prevent costly overruns later in the development process. An iterative, dynamic cost model that is well informed through technical and

programmatic input is, therefore, a key tool during conceptual, proposal, and review processes. This model can be maintained throughout implementation as a means to inform project management on cost and cost risk.

Parametric Tools Allow Us to Speak the Same Language the Customer Uses

Generally speaking, sponsors review cost feasibility of BAA responses using standard industry accepted models. It behooves the proposing organization to employ the same or similar patterns to anticipate and understand how customer evaluators in space system development competitions will estimate the proposed technical system. By doing so, the proposing organization can (1) be informed ahead of time as to how costly the government may estimate a system to be, and (2) accordingly articulate and defend the cost estimate should there be justified customizations as discussed here. The ultimate goal of any cost proposal is to demonstrate—clearly and objectively—that a proposed mission can be executed within the corresponding BAA's cost and schedule constraints.

Cost credibility is paramount in any proposal evaluation process—data-driven parametric modeling techniques that are transparent, repeatable, and defensible are critical. Without such, proposed costs are likely to be evaluated as conducive to high-cost risk, a show-stopper with any budget-constrained and risk-averse customer. The parametric modeling approach, therefore, serves both sides of the process: during the proposal process, the parametric analyst works with the technical team to ensure the mission concept is feasible within a given cost constraint. During the evaluation process, it allows the estimator and the reviewer to speak the same language and reconcile cost differences should the opportunity be available.

Models Provide a Cost Range, Not a Point Estimate

While this has been discussed to some extent above, it is important to re-emphasize the distinction (and advantage) of providing a potential *range* of costs rather than a single point estimate (see Figure 2.1). This range provides decision makers with confidence levels for a particular cost, for example, we have 70% confidence the program will deliver within budget—*this is different from bottom line reserves*. As shown in Figure 2.1, the point estimate plus reserves falls somewhere in the estimated range of costs and has an associated confidence level; this is a single percentage applied to a bottom-line estimate; the s-curve is the product of a robust and data-driven cost risk analysis. The cost risk analysis incorporates cost, technical, and design uncertainty at the subsystem/instrument level, along with targeted cost risk quantification. It answers the question: *What are the major risks and how do they translate to cost*? The spread of the cost range is commensurate with design phase/maturity: it is more expensive to "buy up" confidence in a proposed cost during conceptual phases where there are many technical unknowns; as the design matures, cost uncertainty decreases.

What Are the Major Cost Drivers in a Parametric Model?

Parametric estimates rely on top-level technical inputs and use CERs based on historical data (cost, technical, programmatic). Over the years, to develop more robust CERs, large industry databases have been created for robotic space missions and instruments.

These are dynamic databases that are continually updated with new (and more detailed) data, designed to be cost and technical data repositories used as resources to identify statistical relationships between technical parameters and cost. There is active research within the space cost estimating community to (1) calibrate industry accepted models, and (2) develop robust CERs/cost methodologies. Available datasets include Cost Analysis Data Repository (CADRe)/One NASA Cost Estimating (ONCE) database (NASA), RedStar (NASA/DoD), and NASA Instrument Cost Model (NICM) (specific to instruments). However, it is important to understand one of the critical limitations of any parametric model/CER: estimates are only as applicable as the underlying data supporting the CER. Balloon missions, small satellites, CubeSats, and smaller missions with greater risk tolerance are currently not well represented in cost databases because of limited sample sizes. For these cases, alternative estimating methodologies (i.e., BUE) should be explored. Ongoing data collection and analysis should address this limitation going forward.

Hardware Models

The majority of industry standard modeling tools focus on flight system hardware (spacecraft and instruments). This makes intuitive sense, as hardware development is the primary cost driver for any space mission/system. Hardware drives required technology development cost (and cost risk), design and schedule uncertainty, testing requirements, mass, and power, etc. It is therefore not surprising that the strongest statistical relationships between technical parameters and cost are in hardware development. Detailed and repeated analyses also continue to confirm that other major mission cost elements (Program Management, System Engineering, Mission Assurance, and Integration and Test) are driven by hardware development costs.

Analysts often use multiple hardware modeling tools and cost analogies as estimate cross-checks and to inform cost risk distributions. Major inputs to hardware models include

- Mass (subsystem to board level, depending on design maturity), quantity, TRL, heritage, # of prototypes/Engineering Models (EMs)
- Major COTS procurements (TRL-9)
- Majority of these inputs are found in standard mission Master Equipment Lists (MEL)
- Design Life

However, echoing earlier sentiments that model output must be properly interpreted and customized to reflect the technical design in question, there are additional cost drivers that must be addressed in a robust modeling process; estimates can be adjusted using analogous cost data to reflect these drivers, including (but not limited to)

- Mission reliability/Principle Investigator (PI)-Led (requirements)
- Destination (earth orbiting, deep space, etc.)
- Environmental concerns (e.g., radiation, thermal concerns)
- Organizational structure (e.g., multiple organizations versus in-house efficiencies)

Nonhardware Estimating Methodologies

There are multiple—and costly—mission elements that are not estimated using the hardware-focused cost models. "Wrap" Costs (PM/SE/MA) are well predicted as cost-to-cost factors, generally meaning they are considered cost as a percentage of the flight system (hardware plus Integration and Test). It is important to employ a cross-check estimate using a comparison to actual costs from an analogous mission, given the generic nature of the primary estimating methodology. Remaining Work Breakdown Structure (WBS) elements (e.g., Mission Operations [MOPs], Science, Ground Data System [GDS], System Performance) can be estimated as direct cost analogies or BUE as they tend to be very mission specific; parametric tools for these elements are not widely available. For most proposals, an analogy based estimate with a BUE cross-check (or vice versa) helps lend credence to the proposed cost; a single estimate is still not ideal, even for Level Of Effort (LOE) activities.

Products at Lifecycle Stages

Parametric analyses are critical through all mission phases, from conceptual mission development through CDR. Table 2.4 shows the major role of the cost model at major mission milestones.

As the design matures, and there is increased certainty in project specific requirements (labor, subcontracts, materials, schedule, etc.), BUE becomes a more appropriate estimating methodology. This transition is depicted in Figure 2.2.

TABLE 2.4

Cost Model Contributions at Major Mission Milestones in Early Design Phases of a Future Hardware Build, Parametric Modeling Techniques Are the Preferred and Primary Estimating Methodologies

Lifecycle Stage	Parametric Role	Product
Conceptual design	Assess cost feasibility/cost trade studies	Estimate along with likelihood of delivering within a given cost
Proposal	Primary parametric estimates	Can we credibly propose given cost cap?
Study phase	Lifecycle estimate given technical design/trades	Proposed cost methodology, documentation, and detailed basis of estimate
PDR	Support review process with independent assessment of cost/schedule	Full mission estimate, along with Joint Confidence Level analysis (JCL—integrates cost and schedule estimates)
CDR	Support review process for cost and schedule	Mission estimate with documentation
Throughout	Cost/technical trades; cost-risk analyses	Various

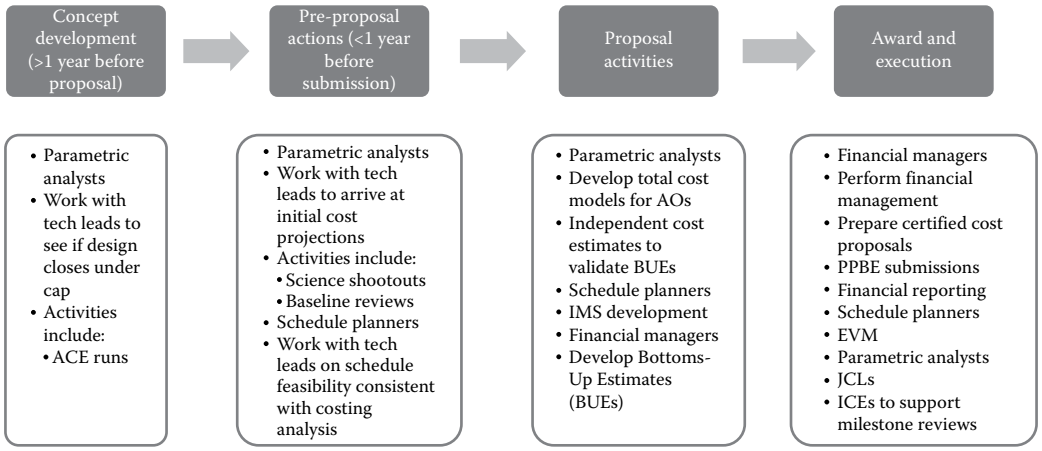


FIGURE 2.2
Estimating methodologies through the project lifecycle.

Parametric Modeling Bottoms-Up Estimates

As the actual proposal submission date approaches, and certified proposal costing needs to be employed in order to ensure that the customer's contracting officer receives the documentation necessary for the proposal to be deemed compliant, financial or resource managers (FMs) will work with PjMs to develop a more concrete bottoms-up estimate that will incorporate the following:

- *Labor*: Staff hours and staff months (possibly by named individual) phased by month and year
- *Material*: A detailed listing and costing of the requisite equipment and parts necessary to build the flight hardware in question, including vendor quotes, website pricing, catalog pricing, etc.
- *Subcontracts*: Proposals from major subcontractors should be included to justify the cost of outsourcing work required to build the space system where the specific core competency is not available in-house
- *Travel*: A discrete listing of all trips to be taken by team members over the life span of the project or a CER that takes the total travel incurred on an analogous project divided by the total direct labor incurred on that project and applies this percentage against the direct labor being proposed to determine the amount of travel to propose
- *Miscellaneous other direct costs*: Any ancillary costs directly related to the space system effort in question, that is, publications costs, consultants, special test equipment used to ensure the flight hardware materials meet the requisite customer specifications, etc.

As stated earlier, bottoms-up proposals take significant time and energy to develop but are required when submitting certified costs to a contracting officer.

A standard approach in developing a BUE is to first establish a WBS, which will serve as the basis for how the work will be managed and the hardware development will be tracked. Immediately subsequent to that, a project schedule should be developed. The schedule will help the PjM in discussions with the technical staff as to what resources are needed to meet the schedule requirements. By developing the schedule prior to costing the effort, it allows the project to ensure costing efforts integrate well with the technical staff's ability to perform the required tasks in the timeframe provided. The requisite labor and nonlabor resources are then applied against each activity in the schedule, allowing the PjM to then "price" the effort and determine whether the total proposed costs are outside the budget limitations, resulting in the project team reassessing what activities might need to be descoped in order to stay within the customers constraints, or identifying whether any task duplication might be occurring, allowing for a broader streamlining of the effort required to consummate the activities needed to deliver the space system "on time and budget."

Cost credibility is paramount when discussing the virtues of parametric modeling. By the same token, it is critical for pricing efforts using BUEs. Contracting institutions will require proposals to incorporate detailed Basis of Estimates (BOEs) for each cost element (labor, materials, subcontracts, travel, etc.) to justify the costs. A BOE is an explanation of the rationale used to produce the cost estimate. It includes logic, data, methodology, and calculations used to determine the resources. The basis of the estimate should provide enough information to the reviewer for them to analyze and evaluate cost credibility.

Conclusion

Parametric cost models (estimates and cost risk analyses) have critical roles during all mission phases, but particularly during early program milestones. Robust estimates and risk analyses are data driven and customized, allowing assessment of cost feasibility from conceptual phases through mission implementation. Additionally, models are continually improved as data collection processes become more rigorous. Ultimately, proposal cost credibility is key to project award, and a low cost-risk assessment requires transparent, defensible, repeatable estimates. The model is a crucial program management tool long term—it quantifies risk, focuses risk reduction activities, informs cost/technical trades, and arms the customer with critical cost data for funding allocations.

3

You're Awarded a Contract! Now What?

Kimberly M. Griffin and Jack D. Letzer

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Introduction

The lifecycle of project management is defined by *the triple constraint*: cost, schedule, and scope. This chapter will help Project Managers (PjM) manage the cost dilemma. Total costs are a combination of direct and indirect costs. Direct costs are defined as expenditures that have *a single*, *defined cost objective*, meaning, they are costs whose origin can be traced to only one product or service. Once a contract is awarded, prudence dictates a thorough reading of the document in its entirety, as the contents define what is contractually binding. PjMs will need to be aware of several key factors described in further detail: contract type, ceiling and funding amount, statement of work (SOW), the period of performance, Contract Data Requirements Lists (CDRLs), and governing documents (e.g., DD254).

Contract Award

Contract Type

Awards are received under several different contract types depending on the amount of risk the customer is willing to absorb and how much risk the customer prefers to pass on to the contractor (aka vendor). The riskiest contract type for any contractor, and as a result the

least risky for the customer, is a *Firm Fixed Price* (*FFP*) award. Under this type of contract, the contractor is bound to deliver the end product for the stated value of the contract award. FFP contracts are typically used when the said product can be clearly defined. In the space industry, if a contractor is awarded an FFP effort under which they will deliver, for example, a CubeSat for $2M, expected to perform X, Y, and Z tasks, then the contractor is *bound* to provide a CubeSat that *shall* perform X, Y, and Z tasks, where the customer will pay $2M, no more, no less. If, when developing the CubeSat, the final cost equates to $3M, the customer will only pay the contractor $2M, resulting in only a 67% recovery of incurred costs with no profit. On the other hand, if the CubeSat ends up costing only $550K, the customer will still pay the contractor $2M, allowing for a full recovery of costs with a $1.45M profit!

One cautionary note as it relates to FFP contracts: Vendors are wise such that if the customer has any kind of engineering change proposal, the vendor will likely seek an immediate fee bearing increase to the contract value as a result of the additional risk the project is taking on. If enough of these occur, this contract type could be more risky to the customer than other vehicles to be discussed here.

The next contract type on the risk spectrum is Time and Materials (T&M). Under this scenario, the risk borne by the customer has increased above FFP, but not quite as much as a Cost Plus (CP) contract to be discussed here. With T&Ms, a customer is paying a specific hourly rate for different labor categories. This hourly rate should cover the worker's salary and associated burdens and fee. The responsibility lies with the PjM to staff the project with workers that have the experience to deliver the product and generate the desired amount of fee. All non-labor costs are reimbursed to the contractor at the cost incurred only.

Cost Plus contracts result in the greatest amount of risk to be borne by the customer. This type is used when the end product cannot be clearly defined, such as development efforts where limited heritage exists from which to base the current hardware build effort. In a CP project, the contractor is required to provide their "best effort" in performing the SOW. The customer will reimburse the contractor all allowable costs up to the negotiated dollar amount (i.e., the contract ceiling). The fee is paid to the customer in addition to incurred costs and can come in various forms: fixed fee, award fee, incentive fee, no fee, etc.

The final type of contract is the Level of Effort (LOE) contract and is based on delivering a certain number of labor hours. LOE can come in Fixed Price or CP arrangements; for LOE contracts, it is important to manage both the number of hours performed, (possibly even by labor category, depending on how the negotiated contract is written), as well as the total cost.

Ceiling and Funding Amount

Given a thorough understanding of the contract type, the next contractual criteria that will affect the effort are the contract ceiling and funding amounts. The ceiling is the total cost allowed under the negotiated SOW. The customer may choose to fund the entire contract up to the ceiling amount (fully funded) or may choose to fund only a portion of the said amount at different intervals (incrementally funded). By funding a contract, the customer allocates monies to pay the vendor as costs are incurred. The contractor is not given this funding up front. Under CP terms, as the vendor incurs allowable costs against the specific project, invoices are remitted to the customer, which in turn are paid from the current funding allocation. It is important that the contractor not incur costs more than the funded cost amount or else it is performing work "at risk," meaning that the customer is not required to reimburse the vendor for allowable costs above the funded cost amount. Note that it is recommended that PjMs manage to total cost and not cost + fee. Often, the financial system will accrue fee as costs are incurred. A PjM does not want to be caught managing to total costs plus fee and

find out too late that the financial system has been incorrectly accruing fee, and more costs have been incurred than what was permitted by the contract. The rule of thumb is that if a PjM manages to total costs, the fee will take care of itself.

Statement of Work

The SOW represents what the vendor is contractually obligated to perform. If the customer requests delivery of any item outside of the SOW's scope, then a modification to the existing contract will be required. When the modification includes a change to the SOW, it may also include a change to costs in order to reimburse accordingly for the change in scope. *The contractor is not permitted to be reimbursed for any costs for work performed outside the contractual SOW*. It is standard practice for a customer to ask for work that may appear to be in the SOW but was not necessarily proposed by the vendor. Be aware of these instances, the so-called *SCOPE CREEP*, which occur frequently. The contractor needs to be cognizant of when a modification is required, in order to increase cost or modify the SOW.

Period of Performance

Vendors should be aware of their contractual Period of Performance (PoP). This is the timeframe when the work is to be performed. Work accomplished outside of the period of performance might not be reimbursed. If circumstances dictate that an extension of the period of performance is required, a contract modification will need to be effected.

Contract Data Requirements Lists

CDRLs state what is to be delivered to the customer and at what point in time. The project in question may have a variety of technical CDRLs, but it most likely has at least one financial CDRL. The customer will negotiate what type of financial detail it prefers to obtain. Additionally, for Government customers, a disclosure of indirect as well as direct costs may be required; however, in a Fixed Price contract, the contractor might not be required to report its financial status in detail, since the risk of the underlying work to be performed is likely relatively low. The PjM will have to work closely with the assigned Financial Manager (FM) to provide the necessary information to the customer to satisfy the contractual deliverables. Figure 3.1 is an example CDRL.

DD254

For the U.S. Government contracting, the DD254 form authorizes a contractor access to proscribed information in order to deliver a product or service. It identifies circumstances under which a contractor will have access to classified information, material, or equipment. The DD254 provides specific authorities for performing classified or similarly sensitive activities and identifies restrictions on access or additional measures the contractor will need to take in order to perform the contract.

Government Contracting versus Industry Contracting

Regulations and reporting requirements are different for the U.S. Government (USG, or the Government) versus Industry. If the customer for a particular contract is the Government, the contractor is held to the *Federal Acquisition Regulation* (*FAR*). The FAR provides

1. LINE ITEM NO.	2. CDRL TITLE	3. FREQUENCY	4. SUBMISSION DATE	5. COPIES
1	Contract Monthly Progress Report	See Remarks	See Remarks	See Distribution
	6. DATA TYPE: ☒ Scheduled submittal ☐ Submittal upon request ☐ Submitted upon update ☐ Gov't Approval Required			
	7. DISTRIBUTION Contracting Officer's Technical Representative (COTR), M/S 203-18 (1 copy) Contracting Officer (CO), M/S 241-1 (1 copy) Resource Analyst M/S 200-8 (1 copy)		8. REMARKS The Contractor shall provide the Government with a monthly technical management, technical performance, and business management, summary for the contract. The report shall contain, but is not limited to, the following: brief status of what was accomplished during the month, significant activities and developments, issues and problems encountered, activities planned for following month. Delivery date: 10 working days after the end of each month	

1. LINE ITEM NO.	2. CDRL TITLE	3. FREQUENCY	4. SUBMISSION DATE	5. COPIES
2	Task Order Monthly Progress Report	See Remarks	See Remarks	See Distribution
	6. DATA TYPE: ☒ Scheduled submittal ☐ Submittal upon request ☐ Submitted upon update ☐ Gov't Approval Required			
	7. DISTRIBUTION COTR, M/S 203-18 (1 copy) CO, M/S 241-1 (1 copy) Task Requesters (1 copy of each of their task(s))		8. REMARKS The Contractor shall provide the Government with a monthly technical management, technical performance, and business management, summary for each task (s) group by task requester. The report shall contain, but is not limited to, the following: brief status of what was accomplished during the month, significant activities and developments, issues and problems encountered, activities planned for following month. Delivery date: 10 working days after the end of each month	

FIGURE 3.1
Example of Contract Data Requirements List (CDRL).

guidance on what is permissible and not permissible under a Government contract. FAR Part 31 is of particular importance and discusses which types of costs are allowable to a specific project. For example, costs that have an identifiable objective, such as labor tied to the development of a specific item for a build, are deemed to be allowable and charged directly to the contract. Costs incurred for a company event, such as alcoholic beverages at a celebration, will likely be considered unallowable and paid out of the company's account. If the customer happens to be from private *Industry*, then the regulations are what is stipulated in the contract itself and may or may not be less restrictive than the FAR. When reporting financials to an industry customer, caution should be exercised regarding the disclosure of any company proprietary information, such as indirect rates.

Work Breakdown Structure

One of the most important ways a PjM can manage costs is via the *Work Breakdown Structure* (*WBS*). A WBS should be developed taking several things into account: (1) the level the customer is expecting costs to be reported, (2) how the contractor's financial system aggregates costs, (3) how costs might be stratified (nonrecurring versus recurring engineering), (4) the customer reporting level might not be at the level of granularity required by the technical lead managing the effort, and (5) capture costs at a level that facilitates proposing similar efforts in the future. NASA, a common aerospace industry customer, has developed a simple WBS structure (Figure 3.2) that clearly addresses space system development.

There are multiple ways to develop WBS structures, so each entity must give careful consideration to doing so in a way that best allows explicit tracking of costs and efficiently develop hardware to meet their customer's needs.

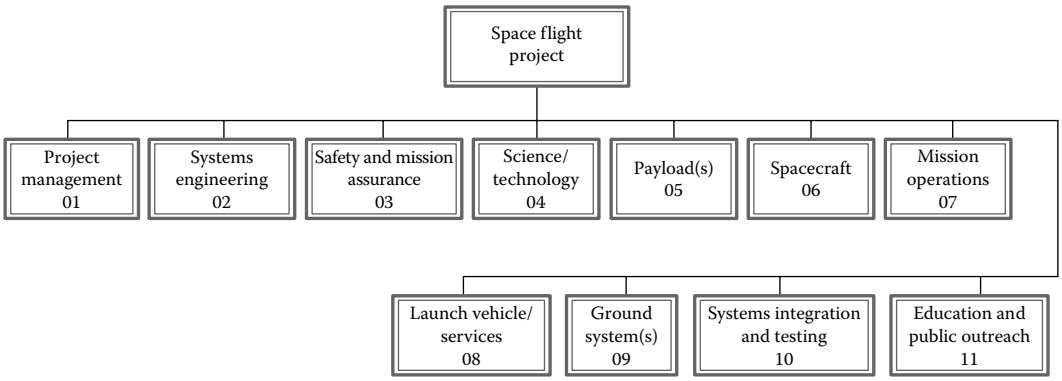


FIGURE 3.2
NASA Work Breakdown Structure (WBS). (Courtesy of NASA.)

Direct Cost Management

Cost Baseline

At this juncture, the PjM should be very familiar with the contractual requirements, developed a detailed WBS, and should be ready to begin managing the costs. The first thing to do is work with the assigned FM or resource manager (RM) to create a baseline. The baseline is the cost performance that the project will be measured against, and can help alert the PjM if he/she is vulnerable to cost overruns or risking scope creep. Reasons to update the project baseline include a change in the contract ceiling value or a drastic change of course that could render comparisons of actuals to the baseline meaningless. A good suggestion would be to use the proposal itself as the starting point for the baseline, although the start month may need to be deferred once *Authority to Proceed* (*ATP*) has been granted by the customer since in most cases the contract start date is usually later than anticipated. Based on how the contract was negotiated, the project team may need to adjust its costs should a negotiated scope change have taken place from what was proposed. PjMs should work with their FMs to create a baseline at the WBS level that can easily track how each WBS is performing to the baseline. If costs are being incurred faster or slower than expected, this will help narrow the search as to where any issue lies.

Operating Plan and Estimate at Completion

The operating plan (a.k.a. Estimate to Complete (ETC).), unlike the project baseline, is updated monthly and should show future planned expenditures.

Labor

Labor should be handled in a "push" and "pull" fashion, assuming each person has an allocation of time and intends to spend accordingly. For example, if a team member was planned for 20 hours in month 1 and they worked 15 hours, then 5 hours of effort will be "pushed" to the right in future months. On the contrary, if a team member was planned at 20 hours in month 1 and they worked 25 hours, then 5 hours would be "pulled" or removed from future months to account for the overrun. If a team member is consistently underrunning her

Initial Operating Plan

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Staff Member 1 - Labor (in Hours)	160	160	160	160	160	160	160	160	160	160	160	160	1,920
Staff Member 2 - Labor (in Hours)	80	80	80	80	80	80	80	80	80	80	80	80	960
Material X		$1,500											$1,500
Material Y				$3,000									$3,000
Subcontractor 1	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$120,000
Subcontractor 2		$300,000			$1,600,000				$500,000				$2,400,000

Oct: Staff Member 1 worked 145 hours and Staff Member 2 worked 85 hours. Actuals of $3,000 has been incurred by Subcontractor 1 and Material X has been paid at $1,210. As a result, the operating plan is updated to "push" 15 hours for Staff Member 1 over the next 3 months. Staff Member 2 "pulls" 5 hours from Nov. Subcontractor 1 "pushes" $7,000 not realized in Oct to the right (Nov). The operating plan realizes the "pull" of $1,210 in Material X to the left and the balance put in Nov. Totals are equal before and after.

Updated Operating Plan after Oct

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Staff Member 1 - Labor (in Hours)	145	165	165	165	160	160	160	160	160	160	160	160	1,920
Staff Member 2 - Labor (in Hours)	85	75	80	80	80	80	80	80	80	80	80	80	960
Material X	$1,210	$290											$1,500
Material Y				$3,000									$3,000
Subcontractor 1	$3,000	$15,000	$12,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$120,000
Subcontractor 2		$300,000			$1,600,000				$500,000				$2,400,000

Nov: Staff Member 1 worked 140 hours and Staff Member 2 worked 80 hours. Actuals of $16,000 has been incurred by Subcontractor 1. Material X had a final payment of $100 in Nov and no future expenditures are expected. Subcontractor 2 is a Fixed Price Subcontract and is behind schedule. The milestone payment of $300,000 is moved to Jan.

Updated Operating Plan after Nov

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Staff Member 1 - Labor (in Hours)	145	140	165	165	165	165	165	165	165	160	160	160	1,920
Staff Member 2 - Labor (in Hours)	85	80	75	80	80	80	80	80	80	80	80	80	960
Material X	$1,210	$100											$1,310
Material Y				$3,000									$3,000
Subcontractor 1	$3,000	$16,000	$11,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$120,000
Subcontractor 2				$300,000	$1,600,000				$500,000				$2,400,000

FIGURE 3.3
Representation of the "push" and "pull" method.

allocation, the PjM and FM will want to make sure they can spend the time necessary on the project and ensure the respective work is being completed. If someone else is consistently overrunning his allocation, then an effort should be made to verify that the person is only undertaking the work that is within their scope, or assesses whether the effort is taking more time than initially anticipated. If the work that was in scope was underestimated, then adjustments will be necessary for other areas to take this into account (Figure 3.3).

Subcontracts

Assume the prime contractor enters into a subcontract agreement with a company and has negotiated the contract value of the work to be performed at $100,000. The operating plan should take into account the expected payment plan for the subcontractor throughout the period of performance. For instance, if the subcontractor has 10 months to perform the work, a logical assumption would be to remit payment at a rate of $10,000 per month for 10 months. Each month actual incurred costs should be reconciled to planned costs with the understanding that unspent funds will be "pushed" to the right with a corresponding "pulling" of any costs where the amount invoiced were greater than anticipated.

Materials

Managing material purchases in the operating plan is similar to managing subcontracts. The PjM will want to be aware each month when reconciling the operating plan to actuals, which materials have been expensed and which materials have yet to be treated accordingly.

Miscellaneous Other Direct Costs

Other non-labor items, such as travel and miscellaneous direct costs, require less management oversight. The PjM may opt to include a monthly allocation for travel and miscellaneous other direct costs based on historical charges for similar projects. Alternatively, information may be available to estimate these costs discretely and, if so, the PjM should work with the FM to take that information into account.

Estimate at Completion

Once the operating plan has been updated, the *Estimate at Completion* (*EAC*) comes into play.

$$\text{EAC} = \text{Actual Expenditures} + \text{Operating Plan or ETC } \left(\text{for future months}\right)$$

The PjM and FM can examine the EAC to determine if total project costs are projecting an over/underrun compared to the awarded ceiling value. If projected costs exceed the ceiling value, then the project has the potential to overrun, and the PjM will need to determine strategies to mitigate future costs in order to bring the EAC back within bounds. If the EAC is lower than the ceiling value, the project has a realistic potential to underrun. If the project is in its early stages, the PjM should consider shifting any underrun into a management reserve account in order to provide the project with a needed cushion that it can tap into during later stages where overruns might be more typical (i.e., Integration and Test). Reserves are discussed in further detail in the section on "Reserves."

Cost Management

Strategies for dealing with a potential overrun can come in a variety of forms. For instance, a detailed examination of each WBS with specific task leads allows the PjM to determine the actual status of the project. If costs are being incurred faster than anticipated, and the effort is still behind schedule, there are a few things the project team can do.

Uncompensated Overtime

If the contract does not limit the number of hours incurred, then a discussion with staff members about working overtime should take place. If the staff is already working full time, then working more hours without additional compensation would help get the project back on schedule without expending additional resources.

Lower Cost Staff

The project team should research having less expensive staff assigned to the project. *Caution should be exercised by the project team, though, as a risk exists of falling further behind on the project, given the use of less experienced staff*. Some staff might provide a lower cost to the project if they are in a different cost center than other staff, and as such, the project team will want to investigate the use of different cost centers within the company. For instance, the contractor may have a situation where on-site and off-site staff members are in different cost pools. On-site staff includes people that work at a recognized company facility. Off-site staff are people that work at a customer's location or possibly from a home office. There are specific criteria for this staff classification and said criteria are defined by the company itself. The principle behind this is that on-site staff is more expensive than off-site staff, due to greater overhead

loadings required for on-site staff members, since the company will need to provide them with office space, computers, utilities, greater management oversight, etc. A customer may be required to provide the same office space, and computers, but in all likelihood, the contractor will charge the customer a lower overhead rate. Unfortunately, the off-site staff member may be fully committed to a specific customer's workload and not have the necessary bandwidth to support the project in question; however it is an option to keep in mind.

In addition to on-site and off-site loadings, there may also be a variety of cost pools to choose. For instance, if some of the hardware building requires the use of expensive, dedicated facilities, these will be accompanied by higher than average burdens since the expensive equipment used will need to be paid for in the form of higher priced burdens.

Idle Staff

Project management will also need to thoroughly investigate just how efficient and dedicated current team members are. Are there staff members that are not contributing as they should to the project? If so, the PjM may want them to stop working on the project and be replaced with staff members who are more productive.

Outsourcing

The PjM should research having some of the work subcontracted out. Often, this avails the project team of a less expensive option since the overhead loadings for some of the work typically allow the project to incur fewer costs rather than performing the work in-house. This is often a difficult by-product of "make-buy" discussions that corporate management needs to address.

Continuing the cost management discussion, if conversely, project management notices an increasing management reserve each month, it could indicate a number of different things: the project might have lower priced people working on it than originally anticipated, a situation may have developed causing the project to fall behind schedule due to staff members not working to the levels originally intended. The PjM will have to determine if enough staff is available to perform the necessary work. One option would be to compare actual costs incurred in the current month to the baseline that was developed for that particular month. If actual costs are lower, it could serve as confirmation that lower priced staff members are working on the effort, causing total costs to be less than anticipated.

If however, actual costs are less than budget *and* actual hours expended are also lower than the baseline, it may or may not mean that lower priced people are working the effort. The first step in this situation is to verify that the project remains on schedule. A situation may have developed in which

- Not enough staff are available to work on the project
- Staff have performed the work in fewer hours than anticipated
- Requirements are still being defined, indicating staff are not able to ramp up as fast as originally planned

If actual costs are higher in the current month compared to the baseline, this could mean more expensive people are working on the project than originally anticipated. The PjM should look at actual hours expended compared to the baseline. Is the project underrunning hours? If so, is work being completed more efficiently? Is the work being completed on schedule?

Commitments versus Expenditures

There are two ways that funds can be allocated for a specific purpose: *commitment* (obligation) and *expenditure* (actual cost). Funds are committed when they have been allocated to another entity (possibly through a purchase order), but cash has not yet been remitted to that entity. An example of this is in *subcontracting*. Just as the prime contractor has a negotiated agreement with the end customer, the contractor may enlist another entity to perform a specific piece of work on the awarded contract. If so, the contractor will commit or obligate funds to that subcontractor so the latter will have an assurance of being paid for work performed. As the subcontracting entity performs the work, it will invoice the prime contractor as its customer, who will then expend funds, or pay them for their services. Funds that are committed should be assumed to be spent. When managing a contract, a PjM should track the project's *uncommitted* balance. For instance, if a subcontractor's services are employed, and $10,000 is committed to said entity, the PjM should "assume" he/she has $10,000 less to spend on other work. Once the subcontractor has completed the work, the FM should closely track the effort to ensure they invoice for all work performed in order to de-commit any funds that were not expended so any residual funds can be used for other purposes.

Reserves

There are a variety of reserve types: contract reserves, contingency reserves, and management reserves. Reserves, in general, are used to cover risks that may or may not become realized on a project.

Contract Reserves

Contract reserves are usually found when contracting with certain federal agencies such as NASA. NASA will require individual projects to carry a separate line item on the contract called "Reserves." The amount of reserves is usually calculated as a percentage of the amount of "*costs-to-go*" of the project. As the project continues through maturity, the contract reserves may decrease.

Example:
Project X is planned to spend $15M in future costs.
Project X is required to maintain 25% of Contract Reserves.

$$\text{Contract Reserves} = \$15\text{M} * 25\% = \$3.75\text{M}$$

Contingency Reserves

Contingency reserves are used to cover identified risks that have not been realized. The amount to hold in contingency reserve can be calculated based on a variety of risk management techniques.

Management Reserves

Management reserve is budget held back from the project by the PjM in order to cover any unforeseen events that may be realized for in scope work and to help mitigate risks. It is up to the PjM to determine the amount of budget to hold back. On average, PjMs hold back

anywhere between 5% and 10% of the total contract value. The amount of management reserve for the PjM to have available on a project depends on the amount of risk the project carries. The greater the inherent risk of the project, the greater the amount of management reserve that should be held as risks materialize.

Property Disposition and Contract Closeout

All contracts should be closed swiftly following physical completion of the work in accordance with applicable regulations and contract requirements. Project closeout involves sending a final invoice, which may be delayed depending on the final acceptance of indirect cost rates. Proper disposition of property is also an important part of contract closeout. Disposition of material may involve one of the following: transfer property to a follow-on contract, return property to the customer, dispose of the property in accordance with proper disposition instructions provided in the contract, or determine that all material purchased was consumed during the life of the project. PjMs should work with their Contracting Officer to ensure all closeout documentation has been completed.

Indirect Cost Management

Although not under direct control of the PjM, there is significant import associated with the impact that indirect costs can have on a project's finances. Before delving into the management of these costs, it is important to understand what they are. Indirect costs are those expenditures that *do not have a defined cost objective*, meaning they are costs whose origin cannot be traced to any individual product or service and are borne to support the overarching efforts of either the specific business unit or the broader organization in question. These indirect costs are broken down into the specific business unit's (1) Overhead costs and (2) General and Administrative (G&A) costs. Figure 3.4 is a breakdown of labor and non-labor costs associated with each of these categories.

Indirect cost categories	
Overhead	G&A
Business unit executive mangement	Executive management (Corporate)
Business analysis	Central financial planning, Contracts, purchasing, internal audit
Information technology (IT)– Laptops/peripherals	General counsel
Quality control	Marketing/business development
Maintenance and repair of equipment/facilities	Bid and proposal
Other miscellaneous expenses	Research and development
	Human resources

FIGURE 3.4
Breakdown of labor and non-labor costs.

Unlike "direct" expenditures, or the labor, material, subcontract, and other miscellaneous direct costs that are directly tied to the space system development effort, overhead and G&A costs need to be "recovered" or charged to the customer in addition to direct costs, as reflected in Figure 3.5.

In this hypothetical situation, the company would invoice the customer a total of ~$254K for all costs incurred in support of the $100K direct salary for the individual (FTE) working on the hardware build itself. This equates to a "wrap rate" of 2.54x the direct salary, a metric that firms use to compare their total cost of delivery with competing entities.

The following dialogue will provide a high-level introduction for calculating both types of indirect rates. First, the process for developing overhead rates to satisfy forward pricing needs can vary across institutions, but in essence follows a simple process:

- *Funding/revenue projections*: Usually monthly or quarterly, senior management teams review the amount of government funding (government agencies, nonprofits) or revenue (profit-driven firms) projected for the fiscal period in question. The purpose of the exercise is to periodically assess the organization's financial ability to meet the project deliverables currently in their queue. The analysis is shown in Figure 3.6.
- *Beginning backlog*: Otherwise known as carry-in, organizations will typically have a set amount of funding to begin a fiscal period prior to additional project funds forthcoming from existing projects. Different entities will have preset backlog

Total labor cost of delivery for full time equivalents				
	Category	$	%	Comments
1	Direct Labor (DL)	$100,000		
2	Fringe Benefits (FB)	$35,000	35%	FB/DL
3	Overhead (OH)	$57,000	57%	OH/DL
4	Total Direct Labour (TDL)	$192,000		DL+FB+OH
5	General & Administrative (G&A)	$36,480	19%	G&A/TDL
6	Cost of Money (COM)	$2,285	1%	CoM/(TDL + G&A)
7	Profit/Fee	$22,848	10%	Fee/(TDL + G&A)
8	Total Cost/FTE	$253,613	2.54	Total Wrap Rate

FIGURE 3.5
Recovery of indirect costs.

Backlog analysis ($M)				
	FY17 1Q	FY17 2Q	FY17 3Q	FY17 4Q
Beginning backlog	$120.0	$120.0	$120.0	$120.0
Total funding/revenue	$240.0	$256.0	$275.0	$268.0
Total expenditures/costs	$250.0	$251.0	$272.0	$269.0
Ending backlog	$110.0	$125.0	$123.0	$119.0

FIGURE 3.6
Quarterly backlog analysis.

ratios or thresholds they maintain. If an entity begins a fiscal period shy of those hurdles, it could signal an early warning of difficult times ahead.

- *Funding forecast by project*: A project-by-project review that focuses on the total projected dollar amount expected for each account. Many entities use a "factoring" methodology to develop their forecast. This can occur in various ways, but a common approach is to forecast the project's funding needs through a "*P Go * P Win*" assessment. In essence, the management team tries to forecast the probability (P) that the customer, or entity sponsoring the directed work, will appropriate the necessary funds for the project in question (Go). That likelihood is then multiplied by the probability or expectation that the entity will be awarded (Win) the competitive bid. The product of the two probabilities then becomes the forecasted funding or revenue amount for the business unit (Table 3.1).
- *Commitments/expenses*: The beginning backlog combined with the aggregate projected funding for the business unit results in the total projected dollars the entity will have at its disposal as it undertakes all of the requisite efforts for each project required to meet key deliverables and space system milestones such as design reviews (e.g., Mission Definition Review, Preliminary Design Review, Critical Design Review, and flight readiness reviews [e.g., Flight Readiness Review, Launch Readiness Review]) . It is important to note that for an entity to have a true, conservative picture of its available dollars, projected expenses should be calculated on a commitment basis, that is, when dollars are obligated and not necessarily paid, that should be considered. For example, if a large material or subcontract buy is planned, the commitment takes place when the purchase order (P.O.) is cut to the vendor, not when payment is remitted, which could occur weeks or months later.
- *Ending backlog*: This total reflects the dollar amount the business unit has on hand at the culmination of the fiscal period once all project commitments have been accounted for. Similar to the beginning balance, this amount will be closely monitored to ensure it meets the entity's metrics, which will indicate the overall fiscal health of the organization entering the following fiscal year.
- *Staffing projections*: The next step in the forward pricing rate (FPR) development cycle for indirect costs requires a project-by-project assessment of efforts required to staff projects in question to meet the respective deliverables. This exercise will likely aggregate all projected full-time equivalents or FTEs (the hours or staff months required to fulfill project needs). Normally, there will be a baseline projection developed at the beginning of the fiscal year. As the period unfolds, an operating plan will be maintained to account for any change in project forecasts (Table 3.2).

  Said staffing projections will then be multiplied by the corresponding labor rates for the individuals working on those projects to arrive at total estimated direct labor $ for the business unit. The total aggregate direct salaries feed the *direct labor base*, the denominator in the overhead rate calculation:

  Total overhead costs / Direct labor base = Overhead rate

  Total overhead costs are comprised to a great measure by those listed in the left-hand column of Figure 3.4.

TABLE 3.1

Funding Forecast by Project

Region	Initiative	P_{win} (%)	P_{go} (%)	FY16 Raw	FY17 Raw	FY18 Raw	FY16 Fcst	FY17 Fcst	FY18 Fcst	Total
Northeast	Project 1	85	100	$2,000	$3,000	$4,000	1,700	2,550	3,400	7,650
Northeast	Project 2	75	75	$20,500	$15,000	$32,000	11,531	8,438	18,000	37,969
Northeast	Project 3	85	95	$1,500	$2,500	$3,500	1,211	2,019	2,826	6,056
Northeast	Project 4	80	90	$30,000	$40,000	$25,000	21,600	28,800	18,000	68,400
Northeast	Project 5	70	100	$600	$600	$600	420	420	420	1,260
Northeast	Project 6	100	90	$500	$500	$500	450	450	450	1,350
Northeast	Project 7	85	100	$550	$550	$550	468	468	468	1,403
Northeast	Project 8	75	95	$250	$250	$250	178	178	178	534
Northeast	Project 9	50	50	$3,600	$3,600	$3,600	900	900	900	2,700
Northeast	Project 10	80	95	$2,000	$2,000	$2,000	1,520	1,520	1,520	4,560
Subtotal				$61,500	$68,000	$72,000	$39,978	$45,742	$46,162	$131,882

TABLE 3.2

Average FTEs by Project Over a Fiscal Year

	Baseline	Current Plan	Current FTE Scenario—FY16 by Month											
East Coast Business Area FTEs	**FY16**	**FY16**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**Jul**	**Aug**	**Sep**
Project 1	214	219	256	257	241	244	232	223	207	200	196	192	189	187
Project 2	9	10	11	15	13	13	10	8	7	7	7	8	8	10
Project 3	22	20	20	18	19	19	22	22	22	22	20	20	20	21
Project 4	29	28	34	33	26	33	30	30	28	27	25	25	24	24
Project 5	11	9	14	11	14	11	12	14	9	7	5	5	5	5
Project 6	50	53	52	57	50	48	48	53	54	52	54	56	58	59
Project 7	9	10	10	10	10	9	9	9	9	9	9	9	9	9
Project 8	6	7	7	8	7	8	7	6	6	6	6	6	5	5
Project 9	8	6	6	5	6	6	7	7	7	7	7	6	6	6
Project 10	20	13	7	10	5	7	12	15	15	17	19	17	19	19
Project 11	42	41	40	43	43	39	40	40	40	40	40	42	43	44
Project 12	7	7	7	7	9	9	6	7	8	9	9	6	5	4
Project 13	4	4	1	3	3	4	4	4	4	5	5	5	5	5
Project 14	3	2	1	2	1	2	2	1	2	2	1	2	2	2
Project 15	10	12	4	6	5	8	10	12	14	15	16	17	21	12
Project 16	36	42	43	35	38	44	44	43	44	44	44	42	41	42
Project 17	2	0	—	—	—	—	0	1	1	1	1	1	1	2
Total	482	483	514	521	491	506	495	493	477	470	463	457	459	455

In a similar vein, G&A rates will be developed by summing up all of the costs in the right-hand column of Figure 3.4, and dividing the aggregate total by all direct labor (DL), fringe benefit (FB), overhead (OH), and miscellaneous direct costs (MDC). The corresponding equation then becomes:

$$\text{Total G \& A Costs} / \text{DL} + \text{FB} + \text{OH} + \text{MDC} = \text{G \& A Rate}$$

Sensitivity Analyses

As mentioned at the outset of this chapter, a good FM will be a very valuable commodity to any PjM. Although Overhead and G&A Forward Pricing Rates (FPR) will be set at the beginning of any fiscal year, it is prudent for any FM and PjM to understand what a variation from the FPRs would mean to their particular project. As the fiscal year and the corresponding reporting periods unfold, the PjM/FM team will need to stay abreast of indirect rate variations to ensure the project anticipates any material event that could have a corresponding cost impact to the project, be it favorable or unfavorable.

For instance, if funding or revenue at the business unit level fails to meet projections, the entity will likely experience a corresponding shortfall in direct (billable) hours, leading to a direct labor base shortfall. Since this is the denominator in the overhead rate calculation, any material reduction will result in an overhead rate increase when costs are "trued up" or reconciled against budgeted costs at the end of the reporting period. A "true up" is a retroactive adjustment that will affect all project-related costs back to the beginning of the fiscal period.

By the same token, if funding or revenue at the business unit level rises above budgeted projections, the entity will likely experience a corresponding increase in direct (billable) hours, leading to direct labor base growth. Any material increase will result in an overhead rate decrease when costs are "trued up" or reconciled against budgeted costs at the end of the reporting period.

Conclusion

Project management in the space industry is a very comprehensive undertaking, requiring an individual to possess significant engineering and scientific knowledge, and to be able to demonstrate judicious stewardship of project finances once the contract period of performance has begun. With respect to the latter, enlisting the support of an experienced FM is essential to the proper execution of a project plan. If nothing else, the following are some over-arching recommendations that would lead to proper financial management of most efforts:

- Assuming the project requires procurements (material + subcontractors), it behooves the PjM to manage projects on a commitment rather than expenditure basis, since that convention will provide a full accounting of all monies obligated by the project at any point in time

- The key to controlling total project costs within the existing scope of the contract is to ensure direct labor hours are within a tight range of the planned amount. The reason being that actual direct labor costs drive all of the allocated indirect burdens, which are priced as percentages of the direct labor total. If the PjM can meet the project deliverables within the assigned budget including management reserves, total project costs should be very close to the amount in the original baseline.

Aside from these suggestions, the ability to anticipate technical changes that will have a materially significant impact on costs will be essential for the project team to execute the project within the budget amount.


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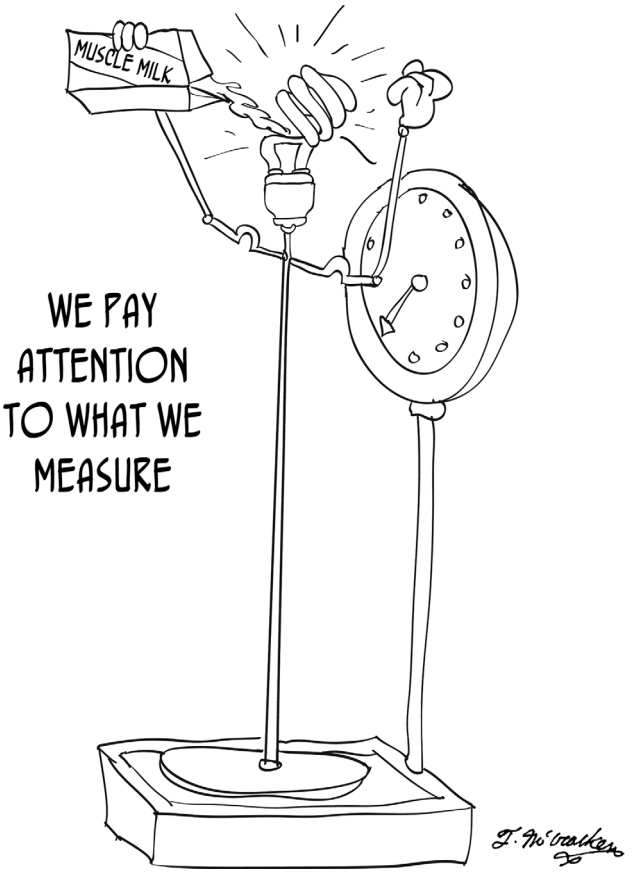
4

It's All about the Plan! (Project Planning and Control Processes and Tools)

corina c. battista

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Some Background on the Importance of Project Planning and Control

Let's start at the very beginning by talking about projects, because there can't be *Project* Planning and Control (PP&C) without a project, right? So, what is a "project?" Its objective is to develop or produce a new product or service, capability, or to expand capacity (i.e., the capacity of a business enterprise). Also, keep in mind, that a project has a definite end; it is, by definition, temporary. There is rarely a case in the real-world where a project does not experience modifications, delays or realized risks along the way. One way to manage the issues and changes that affect a project is through PP&C. Many have heard (and probably even used a time or two) the old adage "failing to plan is planning to fail." Without planning, it is impossible to know if a finish date is achievable or if resource allocation is realistic, which could lead to delays and cost impacts. Ultimately, the success of the project is affected.

PP&C provides a set of time-tested processes and tools for keeping a project on track—no matter what obstacles are encountered during its execution. PP&C provides structure and communication flows by which to manage. Think of PP&C as the way to develop a path through running waters—sometimes those waters will be calm and sometimes they will be turbulent, but with a guiding path, there is less likelihood of lost footing because of trying to figure out where to step.

Failure is mentioned in the very first paragraph of this chapter. A risky thing to do? Maybe. But projects involve risk, sometimes significant risk. PP&C helps to manage those risks as well. Why do projects fail? Reasons can be internal and/or external but are usually a combination of many things, including:

- Unrealistic deadlines
- Changing customer requirements that are not managed properly
- An honest underestimate of effort
- Poor historical data
- Risks—predictable and unpredictable
- Technical difficulties
- Miscommunication among stakeholders
- Failure in project management because of… no or poor PP&C [1].

This chapter seeks to specifically address the last bullet, but with the understanding that well-executed PP&C helps address and mitigate each of these causes for failure. That translates into a better chance for project success. And who wouldn't want that? It is important to note that many factors (such as project size, duration, environment, risk tolerance, and even the level of stakeholder involvement) influence how, not if, PP&C is executed. Fundamentally, these factors only affect the extent to which PP&C is tailored. PP&C, at its core, should be implemented on every project no matter its size, duration, or scope. Intrigued? Let's find out more about PP&C…

Processes: Planning Techniques and Schedule Overview

PP&C starts with an understanding of what work needs to be accomplished to achieve the project's objective. This is best captured in an outline that is high level, customer concurred, and correlates to the Statement of Work (SOW) or the equivalent document that contractually captures what is required to be achieved by the project. Most organizations use a tool for this outline called a Work Breakdown Structure (WBS). Think of the WBS as a table of contents that provides the chapter framework within a book—it eventually informs the detailed schedule that will capture the lower-level effort and steps that are necessary to successfully execute the project. The WBS is defined as a product hierarchy and is usually displayed in a nested written format or in a format similar to an organization chart with boxes. See Figures 4.1 and 4.2 for example graphics [2]. *Fun Fact: Figure 4.1 is the more commonly used WBS format*. Note that the WBS is not an organization chart or detailed schedule, but does provide the backbone on which the schedule is built. It informs both bottoms-up (grass-roots) and top-down (high-level) planning.

A top-down plan starts with the identified major phases and milestones of the summary schedule, then breaks down those high-level tasks into discrete activities at the WBS element level; a bottoms-up plan starts with the lower-level details and works up to the high-level tasks to determine if the effort to be executed fits "within the box" of the prescribed summary schedule. Bottoms-up planning is preferred—at least to establish the initial baseline schedule. (Developing and baselining a schedule will be discussed in more detail in later sections of this chapter.) For those who have not participated in bottoms-up planning before, it can be time consuming and intensive, but it is worth it. The reason for this is that bottoms-up planning includes not only the use of historical data from analogous projects,

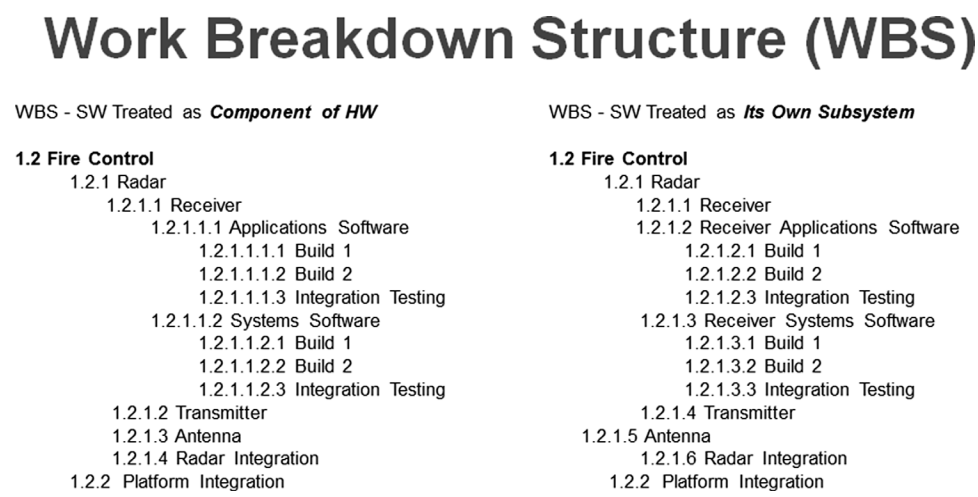


FIGURE 4.1
Example WBS in Outline Form. (From battista, c., Module Lecture 9A "*Project Schedule Planning and Monitoring*," from EP Course "Software Engineering Management," JHU-WSE, Baltimore, MD, 2011. With permission.)

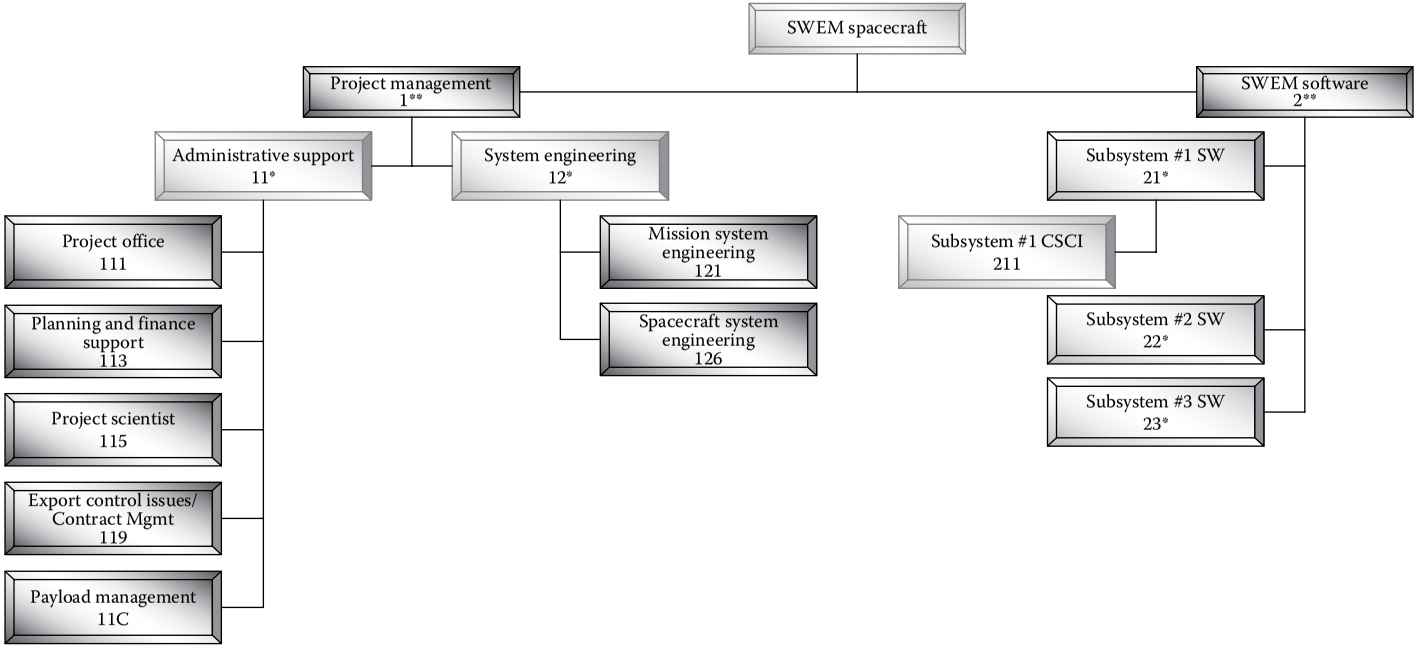


FIGURE 4.2
Example WBS in Organizational Form. (From battista, c., Module Lecture 9A "*Project Schedule Planning and Monitoring,*" from EP Course "Software Engineering Management," JHU-WSE, Baltimore, MD, 2011. With permission.)

but subject matter expert (SME) inputs and estimates as well. Preferably, at least one SME should be consulted for each major subsystem, component or function of the system or service being developed. These SMEs are people who have worked on similar efforts in the past or have unique expertise in similar fields so that their legacy knowledge can be leveraged for more accurate estimates. Bottoms-up planning starts with a quality WBS and involves estimating key pieces of data (such as durations and resource needs) for detailed activities that are incorporated into the schedule to "fill in the outline."

So once there is an agreed-upon and stable WBS, it's time to develop the lower-level schedule. What is a schedule? It is the "document that defines what work must be done, and when, in order to accomplish project objectives on time [3]." *Fun Fact: When combined with a Technical Plan and Cost Plan schedule forms the Project Plan* [3]. A detailed schedule that traces to a high-level summary of the effort required to be executed is one of the most important pieces of a project. Bold statement, yes, but it's true. Well-executed planning is the linchpin of project management. This is because of the versatility of the schedule—it is a communication tool, a strategy, and a guide to developing the project cost estimates for all resources as well as to effectively and efficiently applying those resources throughout the project lifecycle execution. The schedule needs to be comprehensive, accurate, and realistic. For organizations with an Earned Value Management (EVM) requirement, the schedule informs performance measurement. It can also be used to explore risk mitigations, what-if scenarios, and trades as well as manage change.

Processes: Integrated Master Schedule Development

Curious about what an Integrated Master Schedule (IMS) is and how it differs from a schedule? Good. Here's the answer: both are time-phased, linked, traceable to the SOW, and should be complete, accurate, and realistic. However, a schedule tends to be standalone. It focuses more on milestones and tracking them. An IMS does all of that and also incorporates resources and risks. In other words, the cost estimates, resource requirements, and risk considerations are integrated with the schedule's time-phasing to create an IMS. An IMS can, therefore, be used to manage resource needs, resource constraints, and schedule risks. Now it's time to discuss how to develop such a fearsome and comprehensive plan.

There are several software tools that exist to aid in the creation of a detailed schedule. The more popular ones are Microsoft Project©, Primavera©, and Open Plan©. Which tool is chosen for use is usually determined by a combination of the project needs, the managing organization, and possibly the customer. Once the WBS has been laid into the chosen scheduling tool, there are various pieces of information that will be crucial to building that comprehensive, accurate, and realistic plan. Having the SOW handy is important. Start by laying in the tasks to achieve what is promised in the SOW by filling out each WBS element. Capture the activity for each WBS down to a manageable level. What is a manageable level? It should be commensurate with the level of schedule risk. And it will vary based on the managing organization, the project team, and the project itself, but usually ties to the level of risk aversion espoused by one or all of those elements. The people who "own" (create, status) the schedule or sections of it (hopefully they are the SMEs mentioned earlier) should help define what level of detail they need in the plan to be comfortable managing their efforts. But it is important to keep in mind that "less

detail than optimal reduces visibility and increases schedule risk; more detail than optimal adds excess administration without adding value" [4]. With the aid of SMEs, when laying in the activities to accomplish the efforts of each WBS element, assumptions as to what each task's effort represents, what determines if that task is "complete," and any exit criteria/deliverables for that task should be documented within its notes. This will help with the resource loading and duration estimating of each task. It also helps with the calculation of total slack for each activity. Total slack is defined as the amount of duration that a task in a schedule can be delayed without causing a corresponding delay to the project completion date.

If the project involves major subcontract work (i.e., large dollar-amount or complex, risky procurements), Subcontractors should be required to maintain a native schedule (along with performing risk management) that is incorporated into the project's IMS. This aids with regularly reviewing their performance and data because they should be required to status their schedule—just like is done internally—and then submit it. Since the Subcontractor's schedule will be integrated directly into the IMS, their progress, status, variances, etc., can be reviewed comprehensively as part of the analysis of the entire IMS. If there is an EVM requirement for the project, it should be flowed down to the affected Subcontractors, and the requirements should be applied accordingly. The affected Subcontractors should participate in the EVM process. This may require that the Subcontractors have their own WBS elements to report to which the project team will oversee. In the end, though, major Subcontractors should follow the processes and use the tools laid out in this chapter to help facilitate the project's overall plan and execution. Since Subcontractors are inherently more difficult to manage due to their work not being internal to the managing organization, continued surveillance of them and teaming with them is critical to project success. Treat them as any other subsystem or component within the project, and include them early and often in the planning and execution efforts.

Once the detailed tasks for each WBS element are captured in the schedule sufficiently, the following should occur with SMEs' and major Subcontractors' input:

1. Estimate the duration for each task (by asking "how long will it take to execute this activity?").
2. Estimate what resources will be required to execute each task (by asking "what people, materials/parts, equipment, facilities, procurements, etc., will be needed to execute this activity?").
3. Link the appropriate tasks together (by asking as often as needed until all links are determined: "what activity drives/initiates this task (predecessor) and what activity does this task drive/initiate (successor)?").

It's important to note that tasks without a predecessor or, especially, a successor should be kept to a minimum in the schedule. The reason for this is that if a task is not driving another activity or is not needed by another activity, its existence in the schedule should be reevaluated. Now, there are cases where something standalone (i.e., a document that is contractually required) needs to be tracked or deliverables to/from outside entities (tracked in a plan outside the managing organization's) need to be included to show hand-offs. In those cases, it is acceptable to have tasks without linkages. But again, these should be the exception, not the rule. In cases where links are not feasible, constraints can be used, but they should be soft constraints, and they too should be kept to a minimum. This is the perfect time to talk about links and constraints in more detail.

There are only four types* of activity relationships (aka linkages):

1. *Finish-to-Start* (*FS*): Activity 1 must finish before Activity 2 can begin. This is the most commonly used relationship type and for good reason—it forms a true link showing which activities are actually driving other activities and in what time sequence (Figure 4.3).
2. *Finish-to-Finish* (*FF*): Activity 1 must finish before Activity 2 can finish. There is often confusion surrounding this type of link—it does not mean that Activity 2 will finish at the same time as Activity 1, only that Activity 2 cannot finish any earlier than Activity 1. This relationship type is not used as often (Figure 4.4).
3. *Start-to-Start* (*SS*): Activity 1 must start before Activity 2 can start. There is often confusion surrounding this type of link also—it does not mean that Activity 2 will start at the same time as Activity 1, only that Activity 2 cannot start any earlier than Activity 1. This relationship type is not used as often either (Figure 4.5).

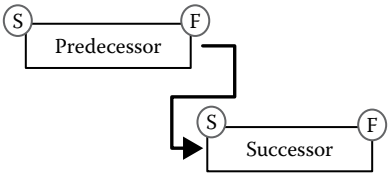


FIGURE 4.3
Finish-to-Start.

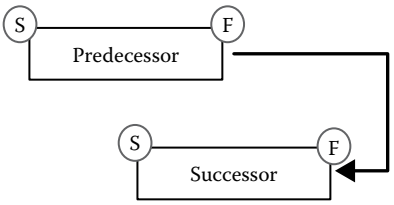


FIGURE 4.4
Finish-to-Finish.

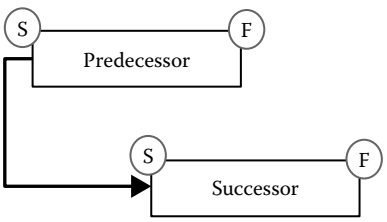


FIGURE 4.5
Start-to-Start.

* The four (4) relationship-type graphics are from the same source [4].

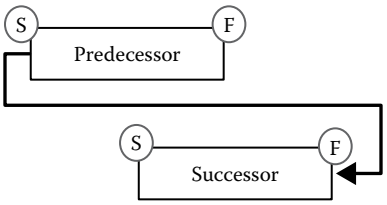


FIGURE 4.6
Start-to-Finish.

4. *Start-to-Finish* (*SF*): Activity 1 must start before Activity 2 can finish. This is the rarest relationship, also for good reason—it does not form a true or driving link and can throw off total slack calculations (Figure 4.6) [4].

There are many ways to represent tasks and relationships within a schedule. The most common are a Gantt chart and a PERT chart. *Fun Fact: The PERT chart was developed by the U.S. Navy in the 1950s to manage the Polaris submarine missile program.* At a high level, the difference between the two is that the Gantt chart uses bars and arrows, while the PERT chart uses boxes and arrows. Examples are shown in Figures 4.7 and 4.8 [5].

On occasion, and as an alternative to links, constraints with or without leads and lags may be used. A constraint works to position the start or finish date of a task to a specific date. It is typically used if there is no logical predecessor to help drive that task and/or if there is a resource availability concern. There are two types of constraints: hard and soft. The comprehensive list is as follows:

- Must Start On (MSO)—Hard Constraint
- Must Finish On (MFO)—Hard Constraint
- Start No Earlier Than (SNET)—Soft Constraint
- Start No Later Than (SNLT)—Soft Constraint
- Finish No Earlier Than (FNET)—Soft Constraint
- Finish No Later Than (FNLT)—Soft Constraint.

Hard constraints should be used rarely. They "lock" in the constraint date so that the task cannot float and will not flow naturally as driven by its predecessor link(s). This type of constraint also causes the total slack to automatically calculate at zero (0) once applied. That makes it difficult to get a true slack position on the constrained task, and, because the total slack is automatically calculated at 0, the task will always show up on the critical path whether it should be there or not. A hard constraint is usually saved for use on (for example) the final project deliverable. This is done because if the contractual date pushes beyond the hard constraint, while the task's date will not move, negative slack will appear. However, there are other ways to show negative slack without locking in the task's date. Deadlines are one way to do so. Soft constraints are another.

Soft constraints effectively do the same thing as hard constraints with the exception of two key things: the task *does* float showing the true date as driven by the task's predecessor(s) *and* the total slack of the task calculates to its actual position… for the most part. In some scheduling tools, like Microsoft Project, the soft constraints, when applied, can drive the total slack to change depending on specific circumstances. If there is a need to apply a constraint, explore the effects of applying different types of constraints to determine exactly

Project WBS	Task Name	% Complete	Duration	Start	Finish	Total Slack	Predecessors	Successors
	SWE Management Course Project	**0%**	**526 days**	**10/31/11**	**11/4/13**	**0 days**		
	Program Milestones	**0%**	**526 days**	**10/31/11**	**11/4/13**	**0 days**		
	System Design Review	0%	2 days	10/31/11	11/1/11	0 days		16,33
	Preliminary Design Review	0%	3 days	6/19/12	6/21/12	351 days	19FS+20 days	5
	Critical Design Review	0%	3 days	10/11/12	10/15/12	272 days	21FS+20 days,	6
	Test Readiness Review	0%	2 days	10/28/13	10/29/13	3 days	29FS+20 days,	7
	Release Final Product	0%	1 day	11/4/13	11/4/13	0 days	31,6	
1.0	**Management and Engineering**	**0%**	**520 days**	**10/31/11**	**10/25/13**	**6 days**		
1.0.1	Project Management	0%	520 days	10/31/11	10/25/13	6 days		
1.0.2	System Engineering	0%	520 days	10/31/11	10/25/13	6 days		
1.0.3	Quality Assurance	0%	520 days	10/31/11	10/25/13	6 days		
1.1	**Hardware**	**0%**	**450 days**	**10/31/11**	**7/19/13**	**76 days**		
1.2	**Software**	**0%**	**523 days**	**11/2/11**	**11/1/13**	**0 days**		
1.2.1	**Radar Software Development**	**0%**	**523 days**	**11/2/11**	**11/1/13**	**0 days**		
1.2.1.1	Analyze Radar Software Requirements	0%	60 days	11/2/11	1/24/12	0 days	3	17
1.2.1.2	Hold Software Spec Review	0%	2 days	1/25/12	1/26/12	0 days	16	18
1.2.1.3	Draft Preliminary Design of Radar Software	0%	80 days	1/27/12	5/17/12	0 days	17	19
1.2.1.4	Hold Radar Software Preliminary Design Review	0%	2 days	5/18/12	5/21/12	0 days	18	20,4FS+20 days
1.2.1.5	Draft Detailed Design of Radar Software	0%	80 days	5/22/12	9/10/12	0 days	19	21
1.2.1.6	Hold Radar Software Critical Design Review	0%	2 days	9/11/12	9/12/12	0 days	20	22,5FS+20 days
1.2.1.7	Develop Radar Software	0%	120 days	9/13/12	2/27/13	0 days	21	23
1.2.1.8	Perform Unit Test of Radar Software	0%	40 days	2/28/13	4/24/13	0 days	22	24
1.2.1.9	Implement and Regression Test Bug Fixes from Radar SW Unit Test	0%	20 days	4/25/13	5/22/13	0 days	23	25
1.2.1.10	Perform Integration Test on Radar Software	0%	40 days	5/23/13	7/17/13	0 days	24	26
1.2.1.11	Implement and Regression Test Bug Fixes from Radar SW Integration Test	0%	20 days	7/18/13	8/14/13	0 days	25	27
1.2.1.12	Perform System Test of Radar Software	0%	20 days	8/15/13	9/11/13	0 days	26	28
1.2.1.13	Implement and Regression Test Bug Fixes from Radar SW System Test	0%	10 days	9/12/13	9/25/13	0 days	27	29
1.2.1.14	Hold Radar Software Test Readiness Review	0%	2 days	9/26/13	9/27/13	0 days	28	30,6FS+20 days
1.2.1.15	Perform Acceptance Test of Radar Software	0%	15 days	9/30/13	10/18/13	0 days	29	31
1.2.1.16	Implement Final Bug Fixes and Regression Testing after Acceptance Testing	0%	10 days	10/21/13	11/1/13	0 days	30	7
1.3	**System Testing**	**0%**	**430 days**	**11/2/11**	**6/25/13**	**94 days**		

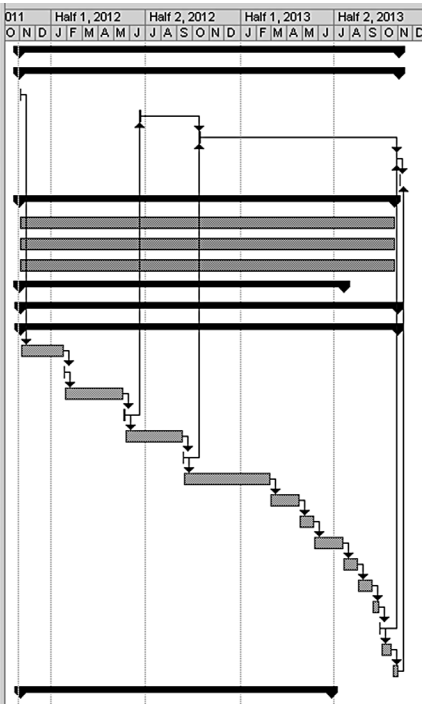


FIGURE 4.7
Example Gantt Chart. (From battista, c., Module Lecture 2C "*Diagram Methods and the CPM*" and Module Lecture 2B "*Scheduling Types and Network Logic*" respectively, from EP Course "Project Management in an Earned Value Environment," JHU-WSE, Baltimore, MD, 2011; MS Project Professional Version 2010. With permission.)

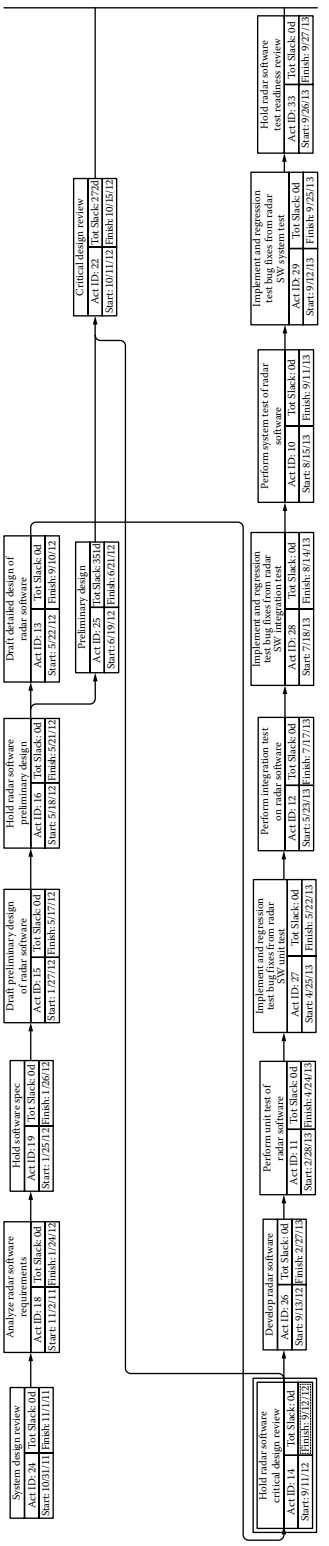


FIGURE 4.8
Example PERT Chart. (From battista, c., Module Lecture 2C *"Diagram Methods and the CPM"* and Module Lecture 2B *"Scheduling Types and Network Logic"* respectively, from EP Course "Project Management in an Earned Value Environment," JHU-WSE, Baltimore, MD, 2011; PERT Chart Expert©. With permission.)

how they will affect a task. But with either type of constraint—hard or soft—the recommendation remains the same: use them sparingly. They can actually cause a "health check" for schedule quality to trip negative for the constraint-indicator criteria. Health checks will be discussed in more detail later in this chapter. Now to enter the other side of the debate: lags and leads.

Lags and leads can be added to logical relationship types and are usually applied to introduce gaps or stagger activities. A positive "gap" or induced duration between the logical relationship is called a "lag." For example, if someone cannot start hanging pictures on newly painted walls at home until the paint has dried for 24 hours, then the "Paint Walls" task would link FS to the "Hang Pictures" task plus 24 hours (FS + 1 day). A negative "gap" or induced duration between the logical relationships is called a "lead." For example, if the "Hang Pictures" task includes the effort of prepping the picture frames with hanging paraphernalia, then the prep work could start prior to the walls being completely dry. Therefore, if the picture frames' preparation can start 4 hours before the walls are ready, then the "Paint Walls" task would link FS to the "Hang Pictures" task minus 4 hours (FS – 4 hours). As there was a caution above for constraints, so too do lags and leads come with caveats. Use them sparingly as well and only to support logical relationships, not to position activities in time.

The last piece of IMS development has to do with resource loading. Why resource load a schedule? For one, while the schedule tasking may be complete, accurate, and flowing logically, without knowing resource needs and availability, it may not be achievable or realistic. Assigning resources helps determine staffing requirements and the timing of those needs. It also helps ensure that resources are being used efficiently and effectively. There are many considerations when "loading" a schedule with resources. First, keep in mind what was mentioned previously: resources are not just the personnel doing the work. Resources include procurements/Subcontractors, materials/parts, equipment, facilities, computer licenses, permits, documents, etc. Second, while it is recommended that resources be "loaded" directly into the scheduling tool of choice (each one has different ways of setting up resources and inputting their corresponding data such as rates, calendars, curves, etc.), there is an administrative "burden" (larger time commitment) associated with managing resources directly in the schedule. This is why some organizations choose to calculate their resource needs outside of the scheduling tool and then only apply the estimates (durations, quantities, etc.) to the schedule manually. Again, however, it's recommended to leverage the scheduling tool as much as possible by loading the resources directly into it to form the IMS.

If resources are loaded directly into the schedule, then scheduling tools such as Microsoft Project allow for different ways to classify a task when determining its duration and work effort. Those three types of tasks are listed in Figure 4.9 [6]. Consider which type of effort most fits the resource situation and then apply the task type appropriately.

Resource leveling occurs when, after loading resources, the level of required resources exceeds the quantity of available resources. In this situation, the resources are said to be overallocated. This propagates the risk that the tasks with over-allocated resources will not start/finish on time or complete properly. This situation is resolved by leveling or "flattening out" the resources so that they are no longer over allocated. This is where leveraging the scheduling tool can save significant time and effort. Most tools can do this, but be careful when applying the tool's resource-leveling feature. The choice of task type (as discussed previously), the tool's option settings, and how the resource data was set up will determine how the tool "chooses" its course of action to level the over-allocated resources. It may lengthen a task's duration, split the task, and so on, depending on how the task and its resource(s) were established.

If your Task Type is …	and you change ... UNITS	and you change ... DURATION	and you change ... WORK
Fixed Units (In other words, there is a set number of resource hours available per period that can be applied to this task, no matter how long it takes.)	Recalculate DURATION (Work/New Units)	Recalculate WORK (New Duration × Units)	Recalculate DURATION (New Work/Units)
Fixed Work (In other words, there is a set number of resource units per period that can be applied to this task, no matter how long it takes.)	Recalculate DURATION (Work/New Units)	Recalculate UNITS (Work/New Duration)	Recalculate DURATION (New Work/Units)
Fixed Duration (In other words, there is a set duration for this task, no matter how many resources it takes.)	Recalculate WORK (Duration × New Units)	Recalculate WORK (New Duration × Units)	Recalculate UNITS (New Work/Duration)

FIGURE 4.9
Task Types for Resource Loading.

It is important to note here that resource risks comes in many flavors, and those risks should be considered when loading and leveling a schedule. Resources may be:

- Unavailable (causing a complete delay)
- Inadequate in quantity (causing a partial delay)
- Inadequately trained (causing rework or delays due to a learning curve)
- Outsourced (causing a lack of control with respect to need dates and quantities)
- Sourced differently (causing rate variations with respect to pay and overhead).

Before resource leveling the schedule, over-allocated tasks should be assessed for all of these and then leveled/managed accordingly.

There is no way to leave this IMS Development section without discussing Schedule Reserve (also known as "buffer" or "margin"). Schedule Reserve should be established as pockets of time to mitigate known unknowns or unknown unknowns (analogous to how management reserve functions with respect to cost in EVM). It is a buffer against risks, like those mentioned above. *Fun Fact: Schedule Reserve can also be defined as the duration between when a deliverable is due and when it is actually available.* Pockets of reserve should be placed at the end of flows leading to major deliverables such as components, subsystems, etc., as well as before the final contractual project deliverable. Many organizations have guidelines on how much Schedule Reserve should be "set aside" (again, based on their risk tolerance stance and other institutional considerations). Customers may even dictate the required amount of Schedule Reserve they want to see allocated. These guidelines/dictates should be followed as a minimum, but risk posture should be assessed to determine if more Schedule Reserve than prescribed is needed on certain deliverables. There is also widespread debate about whether Schedule Reserve should be funded. Again, this will be gated by the project and the managing organization, but it should be funded to the extent possible since this reserve pocket is meant to cover situations where effort is needed but

was not expected. If the Schedule Reserve is unfunded, the use of it may require late-in-the-game requests for additional funding/budget.

Now the fearsome and comprehensive plan alluded to at the start of this section exists. Time to lock in a baseline and start tracking to that plan…

Processes: IMS Baseline Development, Status, and Change Management

A baseline is a snapshot in time. It is essential to EVM, because it's the target against which performance is measured, so it needs to be "locked down." "Snapping" an IMS baseline within the scheduling tool of choice must occur after the planning effort finishes and before the project execution begins. To determine if the IMS is ready for baselining, review the first three sections of this chapter to see if all of the suggested best practices have been achieved. In a nutshell, ask if the schedule is:

- Traceable vertically (linked to the summary-level phases and major project milestones) and horizontally (linked at the same level between components and subsystems/subprojects)
- Resource loaded and leveled (including assigned responsibility for each task in each WBS element)
- Realistic (dates, duration estimates, and resource requirements make sense)
- Integrated (the cost/budget plan and the schedule align)
- Accurate (logically linked with a clear and realistic critical path)
- Complete (all of the discrete efforts promised by the SOW are captured)
- Achievable (there is no negative slack and resources are planned properly)
- Reviewed (holding an Integrated Baseline Review helps!)
- Quality (run those health checks!)
- Controlled (for change management purposes, which will be discussed soon)
- Approved (by the appropriate project stakeholders).

The critical path, an Integrated Baseline Review, and health checks are mentioned in this list. Critical path analyses will be discussed under the Tools section. An Integrated Baseline Review should be conducted with participation by the customer, project team members, independent reviewers, SMEs, and other relevant stakeholders. A review team should be established that will look for all of the criteria listed here. Adjustments will most likely be needed after the review is complete, but those adjustments should only be made if they result in a higher quality schedule. Another way to check the quality of an IMS is to run at least one health check. There are software tools that can aid with this exercise but, at minimum, the check should look for 14 points:

1. Missing Logic (remember the predecessor and successor discussion)
2. Activities with Large Leads or Many Activities with Leads
3. Activities with Large Lags or Many Activities with Lags

4. Relationship Types (as discussed, the FS relationship type should predominate)
5. Hard Constraints (should be minimal and avoided)
6. High Total Slack (usually indicative of missing or poor logic)
7. Negative Total Slack (means a deliverable is not achievable)
8. High Duration (lengthier tasks are more difficult to manage and status objectively)
9. Invalid Dates
10. No Assigned Resources
11. Missed Activities (tasks that were not statused but should have been)
12. Critical Path (is it valid?)
13. Critical Path Length Index
14. Baseline Execution Index (are too many tasks behind schedule for the plan to still be achievable?).

The results of the health check will most likely result in necessary adjustments to the schedule, which means that the health check will need to be run again to check that the adjustments achieved a quality IMS. In fact, the health check should be iterated until all of the criteria show as green or achieve the thresholds recommended in Figure 4.10. This figure shows the suggested thresholds for these 14 criteria or points mentioned [7]. It's important to note that if the schedule development best practices

GASP		14 Point Assessment
Valid	Complete	8. High duration—activities with duration > 44 working days (goal <5%)
	Traceable	1. Logic—activities without predecessors and/or successors (goal <5%) 4. Relationship types—Finish to Start (FS) should be the most common (goal >90%)
	Transparent	2. Leads—(negative lag) distorts the critical path (goal 0%) 3. Lags—(positive lag) excessive size and/or usage distorts the critical path (goal <5%)
	Statused	9. Invalid dates—activities with invalid forecast (incomplete activities to the left of time now) or actual start/finish dates (completed activities in the future) (goal 0%) 11. Missed activities—activities not complete or forecasted to complete as planned (goal <5%) 14. Baseline Execution Index (BEI)—activities completed as a ratio to those activties that should have been completed to date according to the baseline plan (goal >.95)
	Predictive	6. High float—activities with total float >44 work days (goal <5%) 7. Negative float—activities with total float <0 work days (goal 0%) 12. Critical path test—tests the logic in the critical path (goal "pass") 13. Critical Path Length Index (CPLI)—measures the "realism" of the critical path (goal >.95%)
Effective	Usable	5. Hard constraints - activities not designated as As Soon As Possible (ASAP), Start Not Earlier Than (SNET), or Finish Not Earlier Than (FNET) (goal <5%)
	Resourced	10. Resources—if loaded, activities without dollars or hours assigned (goal 0%)
	Controlled	—

FIGURE 4.10
Schedule Health Check Recommended Thresholds.

discussed earlier in this chapter were followed, quality was built into the schedule along the way. But it never hurts to double check.

Since quality is the topic at hand… Processes for managing, maintaining, statusing, and changing an IMS should be documented prior to developing the IMS and then followed rigorously. Reporting requirements should also be determined in advance. That is not to say that ad-hoc reports won't be needed during the project lifecycle, but early determination of the many types of reports that will be needed helps with the development of the IMS. Coding, formatting, and other adjustments may be needed to achieve those reports and should be set up before baselining. If the IMS will be used for EVM purposes, those should also be considered before baselining. At a minimum, verifying cost and schedule integration before snapping the baseline is essential. This means that the time phasing of the schedule should align with the time phasing of the budget plan. The budget plan should also be broken out by WBS, just like the schedule, to facilitate the integration. And the budget planned in a given timeframe should be sufficient for the schedule activities planned during that same timeframe. Resource loading and leveling the schedule helps to assure cost and schedule integration. Balance the need for realism and detail in the integrated plan with the project's risk tolerance, assessment, and degree of flexibility desired.

At this point, the IMS baseline is ready to be locked in. Scheduling tools provide the ability to snap more than one baseline. Prior to the first statusing of the schedule, establish at least one baseline within the scheduling tool. That will create a snapshot of each task's duration, start date, and finish date (at minimum) against which future performance can be measured. The difference between a baseline schedule and a current schedule/plan is that the baseline does not change except with a formal replan (or the execution of a Baseline Change Request, if using EVM). The current schedule is statused regularly with revised, realistic durations, start dates, finish dates, and resource updates based on real-time information and up-to-date learnings. As the project progresses, the current plan will diverge from the baseline plan. It is through these deltas to the plan that performance and potential issues are determined, assessed, and addressed (if necessary). The deviations from the plan need to be analyzed for risk inducement as well as achievability of deliverables to determine if corrective actions need to be taken to continue to be able to achieve the plan.

The IMS should be updated on a regular basis (typically, each month). *Fun Fact: The first status of an IMS converts a baseline schedule to a current schedule*. The frequency of updating the schedule will be determined by many things including the customer's mandate, the managing organization's guidelines, the project's risk tolerance, the EVM reporting requirements (if applicable), project and Leads'/SMEs' needs, etc.…. Key considerations when statusing a schedule should be:

- Status Date (what date should performance be measured against? Time now? Month-end?)
- Actual Start Date
- Actual Finish Date
- Remaining Duration
- % Complete/Physical % Complete*

* % Complete is auto-calculated by scheduling tools based on a task's duration and the passage of time. Physical % Complete is provided by Leads/SMEs based on expert judgment and pre-determined criteria. If logic changes or resource loading needs to be adjusted, those revisions should be done carefully and be documented within the task notes with the reasons why the changes were made (for future reference).

- Logic Accuracy (Is the logic still correct? Is a task still in sequence with its predecessors and successors? Can/should tasks be parallelized?)
- Calendar Accuracy (Has the applied calendar changed due to the need for shifts or resource changes?)
- Resource Loading Accuracy.

Each task that falls within the reporting period should either be given an in-progress % Complete/Physical % Complete, marked as 100% complete, and/or have its start/finish date moved out beyond the status period. The best way to determine the status of a task is to ensure that the underlying goals of that task have been met. Those assumptions that were captured when developing the IMS come into play here. Make sure that each task's described effort, what constituted that the task was "complete," and any exit criteria/deliverables that were documented within the notes have actually occurred. Determining the previous items and, thus, the statusing of the schedule should be done with the Lead/SME's input. Holding face-to-face meetings to input status in real time is the best approach. The Leads/SMEs should come prepared to give status for all past due items *and* be able to assess downstream tasks during the real-time statusing effort. As tasks upstream are statused, their successors will be affected and those should, at minimum, be reviewed to determine that the downstream impact was propagated correctly.

The IMS should be kept under formal version control and changes should be managed, as with any deliverable or official documentation. This is because the baseline's integrity needs to be maintained so that variances can be determined, controlled, and assessed. There are many reasons that a current schedule may vary from the baseline, a subset being:

- Scope change
- Logic change
- Risk mitigation or occurrence
- Activity is missing or taking longer than planned (poor planning or poor estimate)
- Rolling Wave Planning (plan the near-term effort in detail but leave the long-term efforts in longer-duration, high-level tasks to be planned in detail later)
- Use of Schedule Reserve
- Replanning due to issues encountered (known unknowns or unknown unknowns)
- Delays due to resource constraints.

These changes need to be executed in a controlled manner by following processes which should include review and analysis. Some changes may indeed need to be executed and should be incorporated into the schedule to keep the plan current. Some changes may need further analysis before a determination of their applicability is made so the schedule should be used as a "what-if" tool to determine whether such changes are acceptable. In the latter case, a temporary version of the schedule should be saved with the potential changes incorporated so that they can be assessed for their impact to determine the viability and acceptability of the change. Once "approved," those changes can be rolled into the official version of the IMS. In the case of EVM, a Baseline Change Request would need to be executed to allow the baseline to be changed.

Changes will occur, but they need to be managed. When things such as logic or duration change, it's essential to ask why (is a risk occurring? is true status on in-progress tasks being hidden by crunching tasks in the future?) and whether the change is absolutely necessary. In the end, if the change is determined to be warranted, it should be executed… with care. (See the Baseline Change Request discussion in the Tools: Earned Value Management (EVM) Execution section.) Remember: the objective of a baselined IMS is to not only show how the project is performing against the original plan but to also show where the project is currently and how it will realistically be executed going forward based on the learnings to date. These learnings should be used to (re)plan future work as necessary. Revisions and changes should also be assessed for risks (did they induce more? mitigate some?). Schedule statusing is considered a success if it is timely, accurate, analyzable, traceable, and realistic.

Tools: Critical Path, Total Slack Analyses, and Schedule Risk Assessment (SRA)

So, the schedule has been statused… now what? Three key tools to determine the impacts of statusing are critical path analysis, total slack analyses, and Schedule Risk Assessment (SRA). The three go hand in hand (in hand) in fact.

Let's start with the critical path. It is defined as the contiguous path of tasks in a schedule with the longest total duration, thereby determining the minimum end-to-end duration of the project. The critical path is the "longest pole" in the schedule with the least amount of total slack that starts in the present and flows to the finish of the project. *Fun Fact: This does not necessarily mean that the critical path has 0 days of slack* (*a common misconception*)! Total Slack is the amount of time a task's finish date can be delayed without delaying the project's finish date [10]. It is calculated based on the following criteria for each task:

- Early Start (earliest date a task can start based on its linkages and constraints)
- Early Finish (earliest date a task can finish based on its linkages and constraints)
- Late Start (latest date a task can start based on its linkages and constraints)
- Late Finish (latest date a task can finish based on its linkages and constraints)
- Forward Pass (determines the early start and early finish dates of each task)
- Backward Pass (determines the late start and late finish dates of each task).

Total slack is calculated as the smaller value of the Late Finish minus the Early Finish, and the Late Start minus the Early Start [8]. A backward pass *and* a forward pass must be executed to help determine the project's total slack. A scheduling tool will perform these passes automatically when leveraged to determine the critical path within the IMS. However, some expert judgment should be applied when analyzing the critical path results from the scheduling tool. For example, the printing, framing, and hanging of pictures would not be the critical path through the schedule for building a house. Don't just blindly trust the output of the scheduling tool. Double check links, assumptions, durations, and other criteria for accuracy and completeness. The critical path is not necessarily the most complex, most technical, or even the riskiest path in the schedule. But it should pass

the "sniff" test. There should also be a sense developed from working with Leads/SMEs regularly as to what paths may indeed be critical in any given status period. The secondary and tertiary critical paths (the next two flows with the least amount of total slack) should be determined as well, at a minimum. The project's and organization's risk tolerance level and guidelines may dictate if more paths with low slack also need to be identified and what the threshold for that low slack is in determining those additional paths to be identified.

Why is knowing the critical path (and other paths with low total slack) important? There are many reasons, but the two most important ones are that (1) the critical path calculates the project's total duration, and (2) distinguishing the paths with the lowest total slack lets the project team focus on managing the resources and execution of the tasks on those paths more closely. It allows for a form of management by exception, which helps because managing every single path through a schedule would be overwhelming… if not impossible.

Since the critical path is the longest pole (set of tasks to project completion), any duration expansion or date change due to the delay of a task along that path will lengthen the total project duration. If the total slack was low or even zero (0) to begin with, it is possible that statusing could induce negative slack. It is also possible that statusing will cause other paths' total slack to erode and move them onto the critical path or secondary/tertiary flows. Total Slack Analysis should be done to determine if negative slack has been induced and what other flows have had slack erosion or position shifts. Many times, slack erosion is the indication that risks or issues are occurring that may need attention. What exactly is negative slack? It is the way the schedule shows that the project finish date or a major milestone/deliverable/review cannot be met as currently executed.

Some questions to ask when analyzing negative or eroding slack include:

- Is this an error in statusing?
- Which tasks are causing the issue?
- Why are those tasks in trouble? (Sufficient resources? Technical problems? Poor estimate? Priority issue?)
- What can be done to resolve/mitigate the issue?
- Are other activity paths that are related to this one trending toward low slack as well and why [9]?

Some data to review when analyzing negative or eroding slack include:

- Baseline versus current start date
- Baseline versus current duration
- Baseline versus current finish date [9].

Some trends to watch when analyzing negative or eroding slack include:

- Number of critical activities
- Trend of total slack
- Average total slack
- Number of activities on schedule
- Number of activities behind schedule [10].

There are various ways to resolve negative or eroding slack that include, but are not limited to, parallelizing work, adding resources, prioritizing work, and expediting procurements.

The other tool in the analysis tool box is Schedule Risk Assessment (SRA). What is SRA? SRA is "a *risk management process* by which the project team *uses multiple estimates* for durations *to predict the probability of completing the project on time*" [11]. Why do an SRA? First and foremost, risks are inherent in any project, and SRA is the process by which those risks are associated with their corresponding schedule activities. *Fun Fact: It's also good risk management practice, its excellent schedule management practice, and it's even better project management practice to have the tasks identified where the risks may manifest.* This allows the project team to focus on activities that involve higher risk, thus, ensuring insight into possible impacts and potential mitigations/work-arounds should those risks occur. Unresolved or unidentified schedule risks can cause delays and late completions that can cause overruns, missed deliverables, contract penalties and fees, and so on, and even lead to the loss of the contract. One-of-a-kind or research and development projects tend to be riskier by nature. Also, the more procurements and Subcontractors that are involved in a project, the riskier it becomes (due to the lowered level of control over those vendors versus closer management oversight of internal resources). SRA aids in determining paths in the schedule that are the riskiest and, thus, may pose the most problems. SRA also helps determine the likelihood that the baseline will not be achieved. But the most important thing it does, as mentioned here, is integrate risks into the plan—another pitch for the use of an *Integrated* Master Schedule.

How does SRA differ from critical path analysis? Critical path analysis simply adds up the estimates for each task along each path and compares them against the project finish date. SRA identifies the riskiest path(s) and monitors/mitigates it (them) along with the critical path [11]. Critical path analysis with respect to schedule risk is executed by looking for:

- Changes in the critical path
- Changes in the near critical path(s)
- Decline of total slack
- Trending of the three items above [12].

The shortcomings of this approach are that in:

- Relies on single point estimates
- Does not identify the highest risk path(s)
- Is difficult to provide meaningful schedule risk assessments and mitigations [12].

SRA differs in its approach (and thus addresses the shortcomings above) because the steps taken to execute it are as follows:

1. Create a complete critical path
2. Develop three (3) duration estimates: optimistic, pessimistic, and most likely
3. Identify a duration distribution method for all activities
4. Compute the path distribution
5. Evaluate the results, including completion date certainty and high-risk paths
6. Initiate status monitoring [12].

The key differentiator of SRA from critical path analysis is step 2—the development of *three* (3) duration estimates. This ensures a more comprehensive and representative risk analysis via the duration distribution mentioned in step 3. These SRA steps set up a well-disciplined, quantitative risk analysis by using more information about activity duration estimates to provide more accurate path durations. Distribution of various paths at path convergence points or at project end can also be compared. This is important because there is more risk on converging paths. Critical path analysis also cannot handle probabilistic branching easily. Branching is what occurs when the probability of an event occurring changes the flow of the path that the task affected by that potential event resides on. Many different branching scenarios are possible and critical path analysis does not easily deal with those scenarios. Understanding these scenarios aids with Risk Management. It is strongly recommended that the topic of Risk Management be explored in more depth before starting the execution of any project. Like planning, it is essential to project management. Speaking of risk analysis and control, ready for some Earned Value Management?

Tools: Earned Value Management Execution

EVM is a tool that was born circa the 1960s out of the need for improved management of increasingly complex Department of Defense programs. It is now mandated of all Federal Agencies by the U.S. Government as a best practice. There are 32 guidelines having to do with schedule, cost, risk, etc., that must be met to perform EVM. Those guidelines are outlined in the *Electronic Industry Alliance's (EIA-748-C) Earned Value Management Systems Guide.* The *EIA-748-C* document is supplemented by the *NDIA EVMS Application Guide (May 2011)*, *NDIA EVMS Intent Guide (April 2014)*, and *DoD EVM Implementation Guide (October 2006)*. EVM serves not only as an indicator of past performance but also as an early warning system. *Fun Fact: By the 15% completion mark* (*40% for Research and Development*), *EVM can accurately predict a project's outcome with respect to cost and schedule… but only if EVM is done correctly.* And it is important to keep in mind that EVM is just another tool in the Project Manager's tool belt—it should be used in conjunction with, not instead of, all of the processes and tools mentioned in this chapter.

Projects have indeed become larger and more complex over time. The value of EVM is that it introduced the concept of measuring work performance instead of the old way of doing things: simply comparing the planned budget with the actual costs. Comparing the planned budget against the actual costs does not indicate what was achieved (what work was done) for what was spent. This tended to cause a false sense of security, especially if the actual costs were close to or below the planned budget. And it was a reason why programs were getting into trouble. EVM gives insight into how much work was performed for the amount spent. It also organizes the work efforts into a single point of control—a Control Account (CA). A CA is the point of responsibility at the intersection of the WBS and the Organizational Breakdown Structure (OBS—a hierarchical model much like an organization chart that describes the project team assignments). Each CA is managed by one Control Account Manager (CAM). Control Accounts are subdivided into work packages, which is where performance is actually earned. Work packages are effectively the detail-planned tasks within the schedule where efforts are managed and measured.

The fundamentals of EVM can be summed up by understanding its three (3) key terms:

1. *Budgeted Cost for Work Scheduled* (BCWS) is the budget planned for activities to be completed (also known as "The Plan," "Planned," or "S"). The BCWS is derived from the WBS, the project budget, and the IMS. It is laid into the work packages within each control account. The cumulative cost of work packages is time-phased based on the planned dates in the baselined IMS.
2. *Budgeted Cost for Work Performed* (BCWP) is the budget earned for activities actually completed (also known as "The Performance," "Earned," or "P"). It is calculated from the measured work complete and the budgeted costs for that work.
3. *Actual Cost of Work Performed* (ACWP) is the real costs of the work charged against the completed activities (also known as "The Cost," "Actuals," or "A"). It is the actual costs recorded from invoices and the project staff's timesheets.

Don't be intimidated by these acronyms… there are a lot of them. Just keep in mind that the goal of EVM is to determine variances from the baseline. Establishing a baseline as well as achieving cost and schedule integration were described in the "Processes: IMS Baseline Development, Status and Change Management" section. To reiterate: the first step is to create an accurate, realistic, and comprehensive schedule. Voilà! That well-executed planning turns out to be the linchpin of EVM. Since the baseline is what everything is measured against in EVM, the plan needs to be solid or else "garbage in, garbage out": the metrics will be inaccurate, useless, or worse—misleading. Here it is important to mention Rolling Wave Planning again. While detailing schedule activities for the short-term is usually feasible and capable of being done somewhat accurately, longer-term activities pose more of a challenge. The further out the activity in time, the less awareness of what it might actually take to execute it… especially since so many lessons are learned and so many unknown unknowns occur along the way. For this reason, a project team may choose to instantiate Rolling Wave Planning. The near-term tasks (up to 6 months out, for example) are planned in detail as work packages while the far-term tasks (beyond 6 months) are placed in holding bins known as planning packages. Planning packages tend to be longer duration but still should capture at a higher level the efforts that must be completed within that timeframe. Performance cannot be earned on a planning package so it must be detailed out at least a few months prior to its planned start date. Using Rolling Wave Planning tends to cut down on the need for replans and Baseline Change Requests because it gives the project some flexibility in planning the details for far-term efforts. Whether planning packages are used or not, cost and schedule integration needs to be maintained between the budget plan and the schedule at all times.

Once the schedule is established, the baseline budget for the calculated costs (BCWS) can be laid in through resource loading and leveling. This integrated, time-phased cost and schedule plan effectively becomes the Performance Measurement Baseline (PMB). For more information on how to develop the budget/cost piece of a baseline please see section *Parametric Modeling Bottoms-Up Estimates* in Chapter 2 and section *Cost Baseline* in Chapter 3.

Since the linchpin that delineates EVM as unique is the BCWP, how exactly is performance earned? Each work package that carries budget and resources with it should be

given an EV type and statused to measure work accomplishment. Ways that BCWP can be earned are:

- *Interim milestones*—Milestones for a task are determined during planning and then full credit is given at each milestone completion until all milestones add up to 100% for the overall task.
- *% Start/% Complete*—Credit is given at the start and at the completion of the task (e.g., credit can be in the form of 25/75, 50/50, 0/100). This EV type is best used for tasks that complete within one (0/100) or two (25/75, 50/50) status periods.
- *Units completed*—A task is composed of similar units with equal credit per unit times the number of units completed.
- *Percent complete*—Subjective "expert" assessment (by Leads and SMEs) of the percentage of the task that is completed is used; exit criteria should be established with this method. This EV type is best utilized for tasks that finish in more than two status periods.
- *Apportioned*—Work is measured in proportion to other work (e.g., inspection for manufacturing), so the apportioned task earns in proportion to the earnings of the task to which it is apportioned (now *there's* a tongue twister!).
- *Level of Effort* (*LOE*)—Status percentage is based on elapsed duration so BCWS always = BCWP (e.g., used for management or support activities that have no discernible outputs, deliverables, or products).

There is a long-standing debate over whether LOE activities should be included in an IMS. It's recommended that only contractual deliverables or driving tasks within an LOE CA be included in a schedule, preferably as milestones, to ensure the integrity and accuracy of the logic. However, since BCWS is always equal to BCWP so that there will never be a schedule variance *and* since LOE by definition is mainly management and support, there is no value (only added administrative burden) in tracking and statusing LOE in a schedule.

Once status is input on each in-progress or completed work package, the percent complete (based on the EV types) of the statused work packages within a CA is calculated at the summary level and rolled up to an overall percentage for that CA. That percentage is multiplied by the Budget at Completion (BAC) for that CA to come up with a dollarized amount of BCWP for the status period. (Metrics can also be shown in hours for labor efforts, but dollars are more commonly used to keep consistency with non-labor efforts.) The BCWP is then compared to the BCWS and the ACWP for that status period to determine the current period variances via the formulas listed below. The to-date cumulative BCWS, BCWP, and ACWP are also compared to determine the cumulative variances via the same formulas. A Variance at Completion (VAC) should also be determined using the BAC and the Estimate at Completion (EAC). An EAC should be updated, at minimum, quarterly, if not more often. Bottoms-up scrubs of the EAC should also be done regularly.

For a more in-depth look at how actuals for labor, materials, etc., are collected, credited and/or estimated to determine ACWP, please see section *Operating Plan and Estimate At Completion* in Chapter 3. It's important to note that the budget for materials, parts, equipment, or any items that are procured should be planned at the time of receipt (which is how they should also be planned in the schedule) to ensure cost and schedule integration. Facility fees should be planned at the time of use. Estimated actuals can be used to cover any delays or lags in invoicing for these things.

So, to summarize, as statusing begins, the performance is measured (BCWP) against the plan (BCWS), and the actuals are collected (ACWP). These three pieces of data help

determine cost and schedule variances. Since EVM is, after all, a management by exception tool, the proper way to determine which variances need to be analyzed is to first set up reasonable thresholds for Control Accounts based on their size and risk posture. It would be difficult, if not impossible, to manage every single CA in depth. Thresholds help direct the project team where to look for potential issues or risks. These thresholds are represented via dollar amount and/or percentage. It is suggested that both be used. And there are usually different threshold levels for the current EV data (variances within the statusing period) versus the cumulative EV data (variances to date). So, for example, the cumulative threshold to trip a variance might be $50,000 and/or 10% of that CA's budget whereas that same CA's current threshold might be $25,000 and/or 5%. Each CA can have its own threshold, but usually the same thresholds are assigned across most, if not all, project CAs. How are variances calculated? Some more key EVM terms and formulas to learn:

- Schedule Variance (SV) is the difference between the work performed and the planned budget of completed work; it is calculated by the formula "BCWP-BCWS." A SV should be >/= 1, which means that the program is progressing better than or as planned.
- Cost Variance (CV) is the difference between the work performed and the actual costs of the completed work; it is calculated by the formula "BCWP–ACWP." A CV should be >/= 1, which means that the program is costing better than or the same as planned.
- Schedule Performance Index (SPI) is the ratio of work performed and the planned budget of completed work; it is calculated by the formula "BCWP/BCWS." A SPI should be >/= 1, which means that the program is progressing better than or as planned.
- Cost Performance Index (CPI) is the ratio of work performed and the actual costs of completed work; it is calculated by the formula "BCWP/ACWP." A CPI should be >/= 1, which means that the program is costing better than or the same as planned.
- Budget at Completion (BAC—also known as the EVM Baseline or Performance Measurement Baseline) is the original total budget. It is the sum of the budget assigned to all of the work packages in all of the control accounts of a program including LOE CAs.
- Estimate to Complete (ETC) is an estimate of the efforts left to complete the remaining work of the project. This is usually estimated in a bottoms-up fashion from the detailed activity level using Leads' or SMEs' estimates. The ETC plus cumulative Actuals added together = the Estimate at Completion (EAC), which is used to predict the final costs of the project.
- Estimate at Completion (EAC) can be calculated using prescribed formulas (such as an Independent Composite EAC = cum ACWP + [(BAC − cumBCWP)/(cumCPI * cumSPI)]) or estimated in a bottoms-up fashion from the detailed activity level using Leads' or SMEs' estimates. It is used to predict the final costs of the project.
- Variance at Completion (VAC) is the difference between the BAC and the EAC; it is calculated by the formula "BAC–EAC." A positive or neutral VAC means that the project is coming in under or on planned costs.
- To Complete Performance Index (TCPI) is a comparative metric used primarily to determine if an independent EAC is reasonable. It computes the future required cost efficiency needed to achieve a target EAC [13].

The variances that are encountered need to be analyzed, addressed, and reported. A good variance report is one that, as a starting point for analysis, identifies the cause, impact, and corrective action(s) for any variances that have tripped the project's pre-established thresholds. The corrective action(s) should then be tracked for successful closure. If the corrective action(s) are not achieving closure of the issues that caused the variance after the prescribed execution time, a "Plan B" of corrective action(s) should be established and tracked. This process is iterative and should be driven to ground until each variance is either resolved or its trend of growth is stopped.

Keep in mind that variances are caused because the execution of the effort is not occurring as planned. This is not surprising since it is rare for a project to complete perfectly on plan. Sometimes variances indicate that a replan needs to occur and that the baseline (cost and/or schedule) need to be changed to reflect the revised plan going forward. A Baseline Change Request (BCR) has been mentioned previously and should be executed any time a change to the cost and schedule baseline is deemed necessary. A BCR is the documentation that captures the details of the changes to the baseline as well as the approvals for those changes. A BCR form should include:

- The name and numbers of the affected Control Account(s)
- A summary of what the budget was in the affected Control Account(s) before the change, after the change, and the delta between the two
- A description of the change, the need for it, and its impact
- Signature boxes for those who need to approve the changes (i.e., Project Manager; CAM; and [as applicable] EV Manager, Planning Manager, and Financial Manager)
- Any supplemental documents (as attachments) such as a budget report for the Control Account(s) "BEFORE" the change and one for "AFTER" the change.

NOTE: All baseline changes need to be logged in a Baseline Change Log. If Management Reserve is used or returned due to the execution of a BCR, that activity should be tracked in a Management Reserve Log.

Just as there are several scheduling tools to choose from, there are also various EV software tools (engines) that can be used to tie together all of the data mentioned above to create Contract Performance Reports that capture EV metrics in a succinct fashion. While Microsoft Project can be used to calculate EV metrics, the most popular EV engines are COBRA© and MPM© (both made by Deltek). They have customizable reports to meet customer and project team needs.

The last thing to mention about EVM is the need to outline the managing organization's approach to it at the beginning of the project. Just like a Project Plan and Risk Management Plan are created prior to the start of project execution, so should an EVM System Description and Process be created prior to EVM implementation (if EVM is mandated for the project).

That concludes this lesson in "acronym soup." A caveat here: EVM has many more facets to it than could be explored in this section. If the project has EVM requirements, do some in-depth EVM research and immerse the project team in training geared toward the practical execution of EVM. EVM concepts like Management Reserve, Work Statement Authorizations, Responsibility Assignment Matrix, estimated actuals and accruals, as well as the terms and formulas discussed should be well understood as early as possible when

setting up an EVM System and determining what reporting needs to be done throughout a project's lifecycle.

In closing, here are some suggestions for good EVM practices and advice against bad EVM practices. To help facilitate EVM well, do the following:

- Place emphasis on objective BCWP techniques
- Develop Variance Analysis Reports that address specific issues and answer questions such as cause, impact, and corrective action(s)
- As the program progresses, things change. Be willing to alter plans (or replan) but be careful of rubber baselines (baselines that change so often they become meaningless and immeasurable against)!
- Be concerned when there are no variances
- Question a bottoms-up EAC's validity and compare it to an Independent EAC.

And avoid the following:

- Relying on EACs exclusively
- Telling the Control Account Managers (Leads/SMEs) to "get rid of the cost and schedule variances"
- Telling anyone "you better not have a variance" (using EV data to "beat up" the project team)
- Playing the shell game/gaming the (EVM) system
- Never drilling down below Level One of the WBS to manage Control Accounts.

Remember:

- The data is *only as good as* the people reviewing it
- All metrics associated with EV are *only as good as* the underlying planning data (BCWS, WBS, Control Accounts, and Detailed IMS)
- Get it right at the start of the program (hold an Integrated Baseline Review (IBR) even if it is not contractually required).
- The system does not manage the project—People do [14]!

That concludes this foray into Project Planning and Control. Remember to utilize PP&C to ensure project success!

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Much of this material is derived from the course at JHU-WSE, "Project Management in an Earned Value Environment," and were derived from Humphreys and Associates, *Project Management Using Earned Value*, 2nd edn. Humphreys & Associates, Irvine, CA, 2011 with Gary Humphreys' permission.

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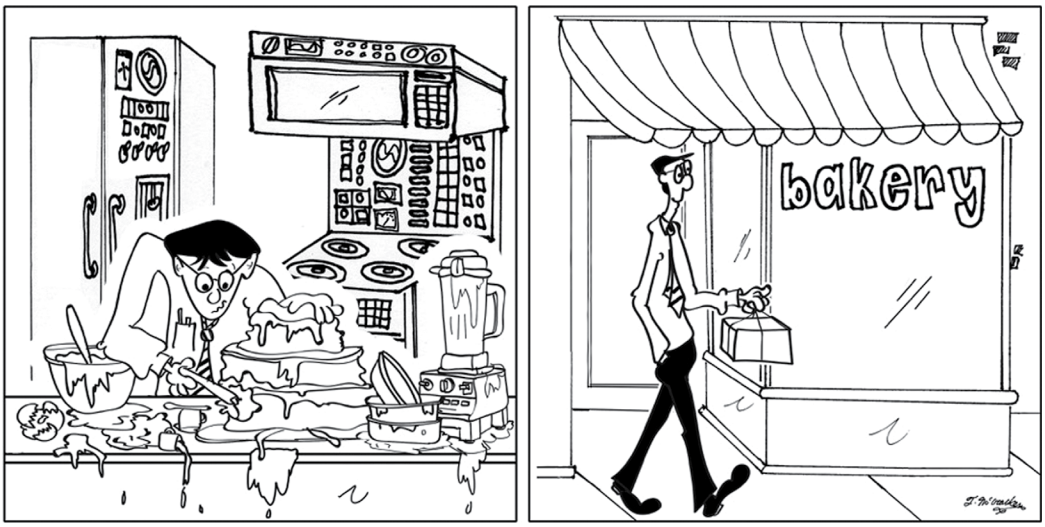
5

Everything a Project Manager Needs to Know about Procurement

Valeree A. Combs

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MAKE BUY DECISIONS CAN GO EITHER WAY.

Introduction

Just as procurement staff rely on the project staff's expertise in rocket science, so too can the project management rely on procurement representatives to handle the details of procurement management. However, a basic understanding of procurement principles goes a long way in helping obtain required purchased supplies and services on time, within budget, and consistent with requirements.

This chapter will provide a Project Manager (PjM) with a basic understanding of their role in the acquisition process by detailing the stages of procurement. While the term Project Manager is used throughout this chapter, many of their responsibilities may be delegated to a Technical Representative whom he/she has delegated authority for the technical oversight and direction of a procurement. This could be a PjM or other individual with adequate technical knowledge to provide appropriate technical oversight and provide technical direction to the contractor.

The procurement life cycle consists of four primary phases, Pre-Award, Award, Post-Award, and Closeout (Figure 5.1).

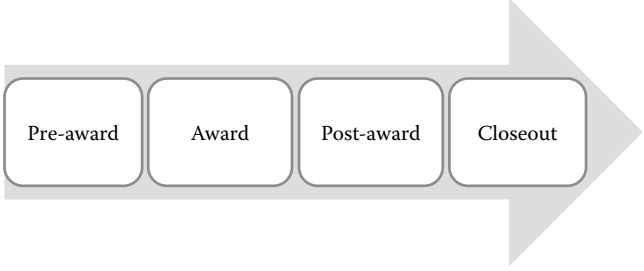


FIGURE 5.1
Four primary phases, Pre-Award, Award, Post-Award, and Closeout.

Within these phases, there are many steps, which are discussed in the sections that follow:

1. Pre-Award
   a. Make-Buy Decision
   b. Market Research
   c. Procurement Planning
      i. Defining the Requirements:
         A. Statement of Work
         B. Statement of Objectives
         C. Performance Work Statement
         D. Specifications
      ii. Developing Acquisition Schedule
      iii. Developing Solicitation Strategy
   d. Solicit Proposals
   e. Source Selection
      i. Technical Evaluation
      ii. Cost/Price Analysis/Cost Realism
   f. Negotiate Price and Terms
2. Award
   a. Award Subcontract or Purchase Order
3. Post-Award
   a. Administer or Manage the Procurement
      i. Preliminary Design Reviews (PDR)/Critical Design Reviews (CDR)/Test Readiness Reviews (TRR)
      ii. Receive and Inspect Deliverables
      iii. Pay Invoices
      iv. Manage Changes to the Agreement
      v. Address any Performance Issues
4. Closeout
   a. Closeout the Agreement
      i. Ensure all Deliverables are Received and Accepted
      ii. Obtain Lien Releases
      iii. Issue Final Payment

Make-Buy Decision

A make-buy decision is the act of deciding whether to build the product in-house or contract for the services from an external supplier or subcontractor. The decision to obtain material, equipment, or services from internal resources or from an outside supplier is typically

determined by the program or PjM, with inputs from in-house resources (shop or lab), financial managers, and procurement staff. The make-buy decision should provide the best value to the customer and the performing organization, taking into account cost, schedule, risk, technical, and other relevant factors.

Factors commonly considered in the make-buy decision are

- Cost
- Delivery and performance schedule
- Maturity and complexity of technology
- Nature of the work (relative to performers essential/proven capabilities)
- Facility and equipment capabilities versus requirements
- Quantity of product, level of service
- Availability of in-house resources
- Capabilities of industry
- International trade compliance and security regulations
- Intellectual property considerations including performer's desire to protect propriety information
- Customer and regulatory restrictions
- Socio-economic preferences or incentives (e.g., small business, veteran status, minority owned)

Procurement Planning

The procurement planning process starts at the moment the decision is made to procure services, subcontract portions of the work, or buy material or parts. It is a critical part of the make-buy decision as market research provides essential inputs such as the ability of suppliers to meet cost, schedule, and technical requirements when compared to in-house resources. During the procurement planning phase, a PjM works with a team of stakeholders to decide what to buy, the timing for items or services to be delivered, and potential sources from whom to buy. In order to make these decisions, it is highly recommended that the PjM and Procurement Representative coordinate on the composition of the acquisition team, including the requesting entity, Procurement Representatives, technical subject matter experts (SME), and even potential contractors if industry inputs are helpful to defining requirements. The Procurement Representative can assist in market research to identify potential sources and determine the most appropriate procurement method.

A well-developed procurement plan reduces the time and expense incurred in the procurement process. A procurement plan includes the following elements:

- All requirements expected to be procured in support of the project, from requirements development through to contract award and fulfillment of the requirement
- Approach and schedule, to include timelines for each purchase necessary to execute and complete and acquisition

- Items or services that can be grouped under one contract or purchase order to take advantage of economies of scale
- Staffing to support the acquisition and oversight or administration processes
- Risks and mitigations strategies associated with the acquisition as early as possible
- Inputs to the PjMs overall schedule for the project

Source Selection Process

Market research can be extremely helpful in shortening the procurement process. Done well, it identifies potential suppliers or subcontractors who can best satisfy the requirements. This research should, at a minimum, include data mining through technical journals to identify commercially available products or services to meet the requirements as well as articles published by organizations leading in research and development. There are other resources also available to identify potential suppliers such as searching GSA Schedules, Government databases for small and disadvantaged businesses, internet searches, responses to Requests for Information (RFI), and industry conferences. Other examples of market research include releasing draft requirement documents to potential bidders to solicit feedback to determine if the requirements are clear, understandable, and feasible or meeting with potential bidders to determine the true capability to satisfy the requirements. Market research should be coordinated among the Procurement Representative, PjM, and SMEs. All market research must be documented in the procurement file.

Competitive Source Selection

Competitive source selection should be pursued whenever practicable. For U.S. Government funded programs this is true regardless of whether the program was itself awarded on a competitive basis.

- If working under a U.S. Government funded prime contract, it is likely that the Federal Acquisition Regulation (FAR) 52.244-5 Competition in Subcontracting is included in the prime contract. This clause requires the prime contractor to select subcontractors and suppliers on a competitive basis to the maximum extent practicable.
- If the performer operates a U.S. Government Approved Purchasing System, the extent that competition is utilized is one of 24 significant factors evaluated in a Contractors Purchasing System Review conducted by the Defense Contract Management Administration (DCMA). For Government programs, if the Purchasing System is not affirmatively approved, the Government may withhold a portion of payments until such time as corrective actions are taken to the satisfaction of the Government. In addition to withholding of payments, the Government can require Contracting Officer's (CO) written consent and/or advance notification requirements prior to the performer's ability to award any subcontract or purchase order valued over the Simplified Acquisition Threshold (SAT), which as of March 1, 2016, is $150,000. Such approval requirements would create a major bottleneck and significant delays in the ability to procure services or supplies.

- Competition drives contractors to propose cost-effective solutions.
- Competition provides alternate and often innovative solutions.
- Competition typically results in better price, contract terms, and schedule.
- Contractors who know they are competing for the award tend to be more agreeable to standard contractual terms and conditions, thereby streamlining the negotiation and award process.
- It is easier to determine a fair and reasonable price when there are multiple proposals.

Single or Sole Source Selection

Although competition is the preferred approach to acquisition, there may be times when it is not feasible. Consult with the Procurement Representative to discuss whether or not a given situation qualifies as a legitimate limited single or sole source justification. As this could have a significant impact on an approved purchasing system, this decision should not be made without due consideration and appropriate documentation.

Defining the Requirements: Developing an Effective Statement-of-Work (SOW), Performance Work Statement (PWS), Statement of Objectives (SOO), and Technical Specifications

According to John Baniszewski, founder of HistoryAndLeadership and former NASA PjM, many studies have analyzed procurements that have run into problems. These studies reveal that the biggest cause of problems is poorly-defined requirements. These studies also show that the more time and effort that is put into accurately defining and describing requirements, the more likely it is that the resulting contract will be performed with fewer cost, schedule, and technical problems. One of the most significant challenges to beginning the procurement planning process is defining what needs to be purchased. It is often difficult to develop a clear SOW for a contractor to propose to when many of the details will need to be worked out during the beginning phase of the project. Various types of requirements documents can be utilized to solicit proposals depending on the maturity of the requirement.

Statement of Work—An SOW describes in detail what must be accomplished. It identifies the outcome and describes how the contractor will accomplish the specified results.

Elements of an SOW include:

1. *Scope*: A brief statement describing the item or service to be procured. This section should not include anything that could be interpreted as giving direction to the contractor, data requirements, specifications, or description of deliverables.
   a. *Background*: It might be helpful to the proposing contractors to include some background information about how the item or service to be procured will fit into the larger project, that is, this is where you may clarify the needs of the project. This section should not include specific task instructions.
2. *Applicable documents*: If the SOW references other documents such as specifications, drawings, quality documents, etc., then they should be listed in the SOW

under this section. All such documents should be identified with a version control number and revision date.

3. *Requirements*: This section should list all technical tasks and subtasks. If a Work Breakdown Structure (WBS) will be used by the project, then the requirements should be arranged in accordance with the WBS. It is recommended that the SOW not over specify the methodology, but instead specify the required outcome. Often times letting the contractor specify the best method to fulfill the requirement results in a more technically robust and cost effective approach. If it is necessary to provide the contractor with detailed technical requirements, a separate Technical Specification document should be created.
4. *The schedule and milestones*: This section should identify significant schedule and milestone events such as Preliminary Design Review (PDR), Critical Design Review (CDR), Test Readiness Review (TRR), Inspections, Program Reviews, etc. During the solicitation phase, it is desirable to list schedules in terms of days after award unless specific dates are critical to the program. Prior to award of the contract, actual calendar dates should be substituted in place of days after award.
5. *Deliverables*: It is important to list all required deliverables, including description, quantity, frequency, format. If the item is not listed as a deliverable, you will not be able to hold the contractor accountable to deliver it.
6. *Location of Work*: It is important to identify where the work will be performed in order to avoid confusion and misunderstandings down the road. Changes in location of work can effect travel cost, export control, and access for inspections.
7. *Period of Performance*: While the schedule and milestones are typically listed in the Contract there are occasions when it is more appropriate to include these elements in the SOW instead, such as when additional detail is required. If it is determined necessary to have these elements included in the SOW, the Procurement Representative should take steps to only reference them in the contract so as to avoid duplication and inconsistency, especially is changes are necessary.
8. *Applicable Standards*: This section should identify any industry or Government standards that must be followed.
9. *Acceptance Criteria*: Acceptance Criteria: Acceptance criteria are often forgotten in the deliverables section, although they are most important. It defines how both parties will know that the item meets the requirements of the contract. It is critical to ensure that both parties to the contract have the same understanding of what will be considered when determining if the contractor successfully met the requirements of the contract and is entitled to full payment.
10. *Special Requirements* (e.g., customer furnished equipment, special coordination with other contractors, security requirements, etc.)

Performance Work Statement—This approach allows the contractor flexibility in satisfying the contract requirements. A PWS identifies specific contract goals, technical and schedule requirements, method for measuring performance, and clear deliverables. In a PWS the requirements section should not contain specific instructions on how the work shall be performed, but rather should state the required outcomes of performance elements.

Statement of Objectives—This approach is more appropriate to use when it is difficult to define how the work should be accomplished or the outcome to be achieved. It identifies the overall objectives of the work to be contracted for, and defines goals rather than

performance requirements. This approach provides potential contractors maximum flexibility in accomplishing the work using their subject matter expertise to develop the most innovative and cost-effective solutions, as well as proposing alternatives to meet the top-level objectives and goals. When using the SOO approach, the contractor's technical proposal usually becomes the SOW that is incorporated into the subcontract. However, the PjM must carefully review the technical proposal for mistakes or weaknesses in the technical approach before agreeing to use this as the SOW in the resulting subcontract. In lieu of the SOO approach, it is not uncommon for some organizations to involve potential contractors in development of a SOW before involving the Procurement Representative. Such an approach is strongly discouraged because it can create an unfair advantage, that is, a contractor could recommend an approach or requirements that only their company can fulfill, and valuable and necessary time is stripped from the solicitation process to ensure that contractors have adequate time to develop well defined technical proposals. Issuing a solicitation with a SOO allows multiple contractors the opportunity to propose a unique approach in order to provide the organization with a wide range of possible solutions.

When using either the SOW or PWS approach to procure highly complex services or solutions, it is recommended that the PjM work with the Procurement Representative to release a draft SOW or PWS to potential contractors to solicit their feedback and improve the requirements document before an official RFP is issued. This allows the contractors the opportunity to identify requirements that limit creativity, unduly impact cost, or unreasonably limit competition.

Technical Specifications

The specification contains explicit requirements of a system, item, or service to be furnished under the contract, defining the requirement that the item or service must meet or exceed to fulfill the contract. Requirements for design, drawings, codes, standards, fabrication, installation, performance requirements, physical/mechanical, environmental, interfaces, and operation and maintenance are usually part of the specifications. Unlike a SOW, PWS, or SOO, which are primarily owned by the PjM, the primary owner of the technical specification is the lead engineer or SME.

Procurement Schedule

Once the decisions have been made regarding what to buy, the PjM, along with the team of stakeholders, planners, and Procurement Representatives, determine an appropriate schedule for the procurement. It is recommended to start at the end requirement (when the item or service must be delivered) and work backwards to determine when the solicitation process should begin and quantify any margin in the procurement schedule to account for delays. The acquisition process can take anywhere from a few days to several months depending on the complexity of the item or service being procured, the completeness of the requirements documents, the quality of the proposals received, the contractor's adherence to proposal instructions, the quality of the technical evaluation of the proposals received, the ability to determine a fair and reasonable price, and the contractor's acceptance of standard terms and conditions.

Source Selection

Prior to issuing a solicitation it is vital to determine how the winner will be selected. If a proposal is solicited from only one source based on a single or sole source justification, then a Technical Evaluation of the contractor's technical proposal will need to be completed by the PjM to determine if the proposal meets the requirements of the solicitation. In addition, a cost or price analysis will need to be completed by the Procurement Representative to determine a fair and reasonable price. The cost/price analysis can take anywhere from a few days to several months to complete, dependent on the contractor's willingness to provide adequate cost detail. If the work is to be performed in support of a U.S. Government prime contract, and the proposed cost exceeds the Truth In Negotiations Act (TINA) threshold, which as of October 1, 2015 is $750,000, then a cost analysis (the analysis of each cost element of the proposal) based on Certified Cost and Pricing Data is required. The contractor's refusal to provide adequate insight as to how they developed their proposal is often the cause of long delays in awarding a subcontract on a single or sole source basis. To mitigate this, it is useful to have early communication with contractors who are bidding concerning what content is expected in the response to allow adequate reviews of their proposal responses.

To assist the Procurement Representative in performing a cost or price analysis, it will be necessary to perform a technical evaluation of the Subcontractor's Proposal. The NASA Technical Evaluation of Sole Source Contractor Proposals Guide, Version 1.0, August 5, 2010, defines a technical evaluation as "…an assessment of the effort a contractor has proposed to satisfy the requirements of the solicitation." The technical evaluation should analyze the information behind the proposed costs such as quantity of labor hours, the skill mix of the labor hours, time scheduling of the effort, quantity and types of material, travel, subcontractor effort, type and quantity of special tooling, and other direct costs (ODCs). This is an important tool used by Procurement Representative in establishing a negotiation position with the contractor for a fair and reasonable price. Upon the receipt of a proposal submitted on a single- or sole-source basis, the Procurement Representative will review it for compliance and forward it to the PjM along with a request for a written technical evaluation. The technical evaluation should be performed by personnel having specialized knowledge in engineering or science and should provide a recommended position as part of the evaluation. It is strongly recommended that the above referenced NASA guide be used when performing a technical evaluation of single or sole source subcontractor proposals over the Simplified Acquisition Threshold as it is very well written and provides good examples of how to perform the analysis.

Evaluation of Competitive Proposals

If the source will be selected based on competition, it is necessary to decide whether the winner will be based on the lowest price technically acceptable approach, or best value approach. If using the lowest price technically acceptable approach, the technical proposals are first reviewed to determine if they are technically acceptable (i.e., they meet the requirements of the solicitation). Award will then be based on the lowest proposed price of those technically acceptable proposals without tradeoffs. Any substantial differences

identified by the PjM between technically-acceptable offerors concerning the benefit or risk associated with a commercial off-the-shelf product should be brought to the attention of the Procurement Representative.

If award will be based on a best value approach, a Source Selection Plan (SSP) will need to be developed, along with evaluation criteria prior to the issuance of the solicitation. The evaluation factors identified in the solicitation should be closely aligned and consistent with the technical requirements of the SOW. The technical evaluation of each proposed offer should provide insight into whether the offeror can meet the contract performance requirements and the perception of risks, which will be used in conjunction with the cost or price analysis to determine the best value. It should also identify the strengths and significant weaknesses associated with each offer. Cost/price should always be a consideration with a weighted value of at least 10% of the overall score. When awarding on a best value basis, it is important to thoroughly document the evaluation and decision making process consistent with the SSP, Evaluation Factors and RFP. As part of the decision process, a rational explanation and justification must be documented to detail how the selected proposal provides the best value. Best value is recommended for all competitive solicitations for non-commercial items or services.

Roles and Responsibilities

Within the U.S. Government, the Contracting Officer (CO) has the authority to enter into, administer, or terminate contracts, but may only bind the Government to the extent of the authority delegated to them through their warrant. The CO has the authority to determine the application of rules, regulations and policies on a given contract and is responsible for ensuring compliance with contract terms. The CO can authorize a Contracting Officer's Representative (COR) to perform certain duties, but cannot authorize the COR to make any contractual commitments or changes that affect price, quality, quantity, delivery, or other terms and conditions of the contract.

While the Federal Acquisition Regulation provides clear limitations of authority for those within the U.S. Government, specifically for the CO and COR, each organization outside of the U.S. Government may have their own policies and delegation of authority. Therefore, it is important to know who has authority within the customer's organization as well as within the subcontractor's or supplier's organizations. Many individuals feel uncomfortable asking this question, but it is highly recommended that contract and/or Procurement Representatives request this information prior to entering into negotiations and certainly before entering into a contract. Contracting through an individual who does not have authority may prevent the performer from binding the subcontractor's organization to perform the contract.

It is also important to understand the roles and responsibilities within the performer/PjM's own organization. Many of the decisions relating to procurement are the joint responsibility of the PjM, technical expert, and Procurement Representative. However, typically an organization delegates in writing certain responsibilities relating to the ability to commit the organization based on position and dollar threshold. A common means of accomplishing this is for the performer's leadership (e.g., Director, Chief Executive Officer, Board, etc.) to issue a delegation of signature authority memorandum relative to spending authority, contractual agreements, and procurement agreements. In addition, analogous

procurement procedures should delineate the responsibilities of those that make up the procurement team, specifically the Procurement Representatives, technical representatives, program and PjMs, and business/financial managers. Procurement representatives are responsible for soliciting, awarding, and administering subcontracts, purchase and delivery orders, and other procurement-related activities.

It is also common for PjMs to be the individuals specified in the contract as having authority for the technical oversight and direction of the procurement. This could be a program manager, project manager, or other individual with adequate technical knowledge to provide appropriate technical oversight and provide technical direction to the contractor. Once a decision is made to acquire supplies or services through the contracting process, a partnership is created between the PjM and the Procurement Representative. This partnership is essential to establishing and achieving contract objectives because these two officials are responsible for ensuring that the contracting process and subsequent contract administration is successful.

Procurement Representatives and PjMs have both separate and mutual responsibilities, with lead responsibility shifting from one to the other during the various stages of the contracting process. During the presolicitation phase, the PjM has the lead and the Procurement Representative supports. However, as this phase ends and the solicitation and award phase begins, the lead responsibility shifts to the Procurement Representative, with the PjM supporting. During post-award administration, the PjM assumes lead responsibility for some functions, and the Procurement Representative for others. Typically Procurement Representatives sign the contract on behalf of the performer organization and bear the legal responsibility for the contract. They alone can enter into, change, or terminate a contractual commitment on behalf of the performer.

As a team, the Procurement Representative and PjM must ensure that the contract is designed to meet clearly defined program requirements. Together, they are responsible for ensuring that, when practicable, competitive sources and small business concerns are solicited, evaluated, and selected; and that the price paid for acquired supplies and services is fair and reasonable. They must establish quality standards and performance measures, delivery requirements, and make sure these metrics are met. PjMs evaluate all proposals submitted, monitor the contractor's performance in reference to the contract requirements, and must report any and all deviations to the Procurement Representative.

The principal role of the PjM is to furnish technical direction, monitor contract performance, and maintain a professional relationship with the contractor. One of the primary functions of the PjM involves issuing technical direction to the contractor. Performance work statements are often inexact, resulting in the need for technical instructions as the work progresses. Technical direction is confined to the requirements document specified in the contract and includes instructions to the supplier necessary for accomplishing the SOW (e.g., clarification of the SOW, additional details, or suggestions). Technical direction does not include authorizing changes to scope as that requires a modification to the contract. This is the responsibility of the Procurement Representative, working closely with the PjM to define the change and negotiate the modifications into the contract.

The PjM should act as the focal point for all correspondence and discussions with the contractor concerning technical direction and issue and document all technical direction that provides specific details and milestones. The PjMs is responsible for ensuring that all technical directions are reduced to writing to avoid misunderstandings and disagreements, to avoid unnecessary costs, and generally to maintain proper control of the contract. A copy of this documentation shall be provided to the Procurement Representative as well as the contractor. The Procurement Representative is responsible for reviewing the

documented technical direction to ensure that it does not constitute a change in scope, which may create a cost impact to the contract.

The PjM plays a critical role in influencing the outcome of the contract administration process. Contract technical administration is an essential activity. The primary role of the PjM during this phase is to provide technical clarification and to monitor contract performance, thus ensuring the performer pays only for the services, materials, and travel authorized and delivered under the contract.

Delegation of a Technical Representative

A PjM is responsible for the technical oversight and management of a subcontract. However, the Project Manager may delegate his/her responsibility for the oversight of a subcontract to a Technical Representative (TR). The TR is often identified in the contract at the time of award with their authorities and duties specified in the contract. The authority of a TR is often limited to providing clarification of requirements documents, or technical direction within the SOW, and determining the acceptability of the deliverables. TRs do not typically have authority to direct a contractor to perform work outside the SOW or change the requirements documents. These activities would require a modification to the contract by the Procurement Representative. If the TR changes, a modification will be issued to the contract in order to notify the contractor.

A substitute or alternate TR may be designated to fill in for the primary TR. Due to the scope or technical complexity of some contracts, "sub-Technical Representatives" may also be designated for specific aspects of the contract. If sub-TRs are necessary, they should be identified in the contract, with their authorities and duties specified in writing. Sub-TRs are the responsibility of, and responsive to, the TRs.

Technical Representative and Procurement Representative Responsibilities as Linked to Project Life Cycle

Technical Representative Role (Pre-Award)

- Develop requirements (SOW and technical specification as applicable)
  - Determine the scope and performance specification, as applicable
  - Conduct market research
  - Identify deliverables and work products
  - Develop a schedule of deliverables
  - Establish period of performance
  - Establish specific acceptance criteria
  - Identify Government Furnished Property (GFP)/Government Furnished Equipment (GFE)/Confractor Furnished Equipment (CFE)
  - Provide in-house cost estimate
- Flow down appropriate security requirements
- Initiate export license or Technical Assistance Agreement (TAA) request, if necessary
- Initiate nondisclosure agreements, if necessary
- Identify specific source selection evaluation criteria for competitive solicitation

- Provide technical evaluation of technical and cost proposals to Procurement Representative
- Assist with negotiations as needed
- Allocate funding resources
- Obtain management approvals

Procurement Representative Role (Pre-Award)

- Work closely with the TR, providing advice and guidance concerning the TR responsibilities listed above
- Assist in identifying potential sources
- Qualify potential bidders based on eligibility to receive awards/subcontracts, past performance, and financial stability
- Develop solicitation documents (RFI/RFQ/RFP)
- Ensure that the solicitation process is fair to all participants
- Ensure that all prime contract/solicitation requirements are incorporated into the RFP
- Ensure that all procurement procedures are followed
- Ensure that the source selection process is followed according to the plan, and that the evaluation process is fair
- Complete the cost/price analysis as necessary
- Prepare formal basis of estimate if necessary to support proposal activities
- Inform the bidders of the outcome of the source selection process
- Negotiate contract price and terms
- Obtain government consent to subcontract as necessary
- Provide government advance notification of intent to award subcontract as necessary
- Obtain executive management approval of subcontract as necessary

Technical Representative Role (Award)

- Clarify technical requirements
- Develop communications paths—technical
- Initiate request for DD254 (authorizing classified work) if necessary
- Initiate visitor control requests as necessary
- Establish status meetings
- Assure contractor work space
- Review TAA and export license for consistency with final contract award

Procurement Representative Role (Award)

- Award contract
- Participate in kick-off meetings as necessary

Technical Representative Role (Post Award)

- Monitor the Contractor's performance on a continuing basis to insure that the Contractor is making acceptable progress in meeting technical, schedule, and budget requirements.
- Receive, inspect, and accept deliverables.
- Provide written Notification of Acceptance of deliverables to Procurement Representative.
- Assure prompt review and approval of draft/final reports.
- Confirm all significant technical direction to the contractor.
- Ensure that proposed changes in scope of work or service are reasonable and necessary and are accomplished by formal contract modification issued by the Procurement Representative.
- Maintain a contract work file including significant correspondence and deliverables (for 4 years following prime contract closeout).
- Monitor financial management controls.
- Coordinate with the program office and Procurement Representative all action(s) relating to funding and/or changes in scope of work.
- For cost reimbursable contracts—provide advance written approval of travel if required under contract terms (obtain government approval if required under prime contract terms).
- Review and verify the contractor's invoices for hours expended and costs incurred.
- Inform the Procurement Representative when a contractor is behind schedule and coordinate corrective action to ensure contract schedule.
- Monitor the contractor's performance to ensure performance is within the scope of the contract.
- Review periodic status reports of work completed, cost incurred, hours expended, and issues noted.
- If nonconforming deliverables are identified, TR must work with the Procurement Representative to notify the contractor and establish a corrective action plan.

Procurement Representative Role (Post Award)

- Review contractor monthly fiscal reports for indications of unanticipated contract risk or need for contract modifications.
- Review monthly invoices for conformance with contract terms and proposed costs.
- Reconcile that contract deliverables are provided in accordance with the contract terms.
- Participate in program meetings as requested by TR.
- Issue notices to contractor relating to contract performance issues.
- Alert TR of need for incremental funding as necessary.
- Negotiate and issue modifications to the contract as necessary.

- Provide advice and guidance to TR concerning contractor performance issues.
- Maintain official contract file until work is complete and ready to be transferred to Closeout Team.
- Prepare contract file for closeout upon completion of contracted work.

Limitations of Technical Representative Authority

The Procurement Representative has signature authority and the TR has technical authority. The division of duties enables a business specialist to assure best business practices and the technical specialist to assure best technical practices. As such, the TR should refrain from doing any of the following:

1. Making commitments or promises to any contractor relating to a contract
2. Encouraging a contractor to incur costs/start work prior to receiving a contract or an executed contract modification for additional work
3. Encouraging, requesting, or requiring a contractor to make changes or take any action beyond the requirements of the contract without an executed contract modification
4. Encouraging a contractor to incur costs under a cost reimbursable contract in excess of those costs contractually allowable
5. Writing contract requirements to the product or capacity of one source
6. Soliciting proposals
7. Modifying any terms of the contract
8. Issuing instructions (oral or written) to a contractor to start or stop work
9. Approving items of cost specifically not allowed by the contract
10. Directing changes (oral or written)
11. Signing supplemental agreements
12. Negotiating cost, schedule, terms and conditions (Ts&Cs), or changes to the contract without the involvement of the Procurement Representative
13. Taking any action with respect to termination, except to notify the Procurement Representative that the action is desired and to assist with the process as requested
14. Authorizing delivery or disposition of Government/Customer-Furnished or Contractor Acquired property
15. Giving guidance to a contractor, either orally or in writing, which might be interpreted as a change in scope or terms of the contrac;
16. Discussing procurement plans or any other advance information that might provide preferential treatment to one firm over another when a solicitation is issued for a competitive procurement
17. Directing a contractor to begin work prior to contract award date

Violation of the foregoing may give the appearance that the performer's organization is not acting in good faith. Commitments made to a contractor by other than duly appointed Procurement Representatives can result in embarrassment, U.S. Government issues with an approved Procurement System, and possible legal action by the Contractor.

Contract Types

There are various contract types that can be used for each acquisition. Working closely with your Procurement Representative to identify which method is most appropriate for the circumstances is highly recommended. Note that the subcontract/procurement can be of a different contract type than the prime contract (e.g., prime contract may be a cost-plus-fixed-fee type and the subcontract could be firm-fixed-price).

Firm-Fixed-Price (FFP) contracts—FFP type contracts are the preferred method of contracting when the items or services to be provided can be clearly defined. This method establishes a fixed price for the items or services to be delivered and shifts the majority of the risk onto the supplier to deliver the product or complete the work on time in order to be paid. As long as the items or service meet the acceptance criteria, the full amount is due to the contractor. For complex requirements, or contracts with extended periods of performance, the team may consider milestone payments or performance-based payments. FFP type contracts are commonly used in both commercial and U.S. Government procurements.

Under a FFP type subcontract, there are three customary payment methods: payment upon completion, payment on a specified date schedule, or milestone payments. Payment upon completion is the preferred method, but may not be feasible if the subcontract covers an extended period of performance. Paying on a specific date schedule is the greatest risk as payment will be due to the supplier regardless of the progress that they have made.

Milestone payments are based on the contractor demonstrating satisfactory completion of an established milestone. These milestones should be clearly defined in the contract in terms of schedule, description, and measurable acceptance criteria. Milestones should be based upon events that are clearly tied to the demonstration of progress. For example, tying a milestone to placing an order for long lead items is less indicative of progress than tying it to actually receiving and accepting the long lead items. The milestone payment schedule should be representative of the value of the item delivered or event completed, not the anticipated costs incurred by that date. It is important to avoid milestone payments that allow the contractor to finance their work with the buyer's money. Keep in mind, once a subcontract is entered into, standard contract payment terms are NET 30 days from receipt of an acceptable invoice after the contractor meets the requirements of the subcontract. If the subcontract is awarded under a U.S. Government prime contract and the subcontractor is a small business your company will be required to pay a minimum of NET 30. A prime contractor cannot even bill the U.S. Government until it has been billed by the subcontractor. There could be as much as a 30-day lag between when a prime contractor receives the subcontractor's invoice and when the prime will invoice the Government. However the customer (or Government sponsor) most likely has NET 30 days from receipt of the prime's invoice to pay. That means that, in almost every case, the prime contractor will be responsible for paying their subcontractors before they receive payment from their customer.

Many confuse funding authorization with payment. Under U.S. Government contracts, funding is authorized, which means a company has the Government's commitment to pay NET 30 days after receipt of invoice for work complete. It does not mean that they have actually paid at the time of funding authorization. The same, then, typically goes for subcontractors under a U.S. Government funded project. The prime contractor authorizes the subcontractor to proceed with work and commits to pay them NET 30 days after receipt of invoice for work complete.

If the subcontract agrees to milestone payments that front load the payment schedule the following risks may occur:

1. It may be necessary to terminate the subcontracted work (either due to cancellation of the program or the subcontractor's unsatisfactory performance) prior to receipt of product or services being delivered. If the money is paid in advance that money will likely be unrecoverable.
2. If advance payment is made to a supplier that is not financially stable, the prime runs the risk of being an unsecured creditor in the event the supplier goes bankrupt.
3. Leverage is lost in getting the job completed on time and to the program's satisfaction if a significant amount of the contract value has already been paid to the supplier.
4. The cost of money is incurred when the supplier is paid in advance; thus the prime may need to either borrow the money or take money away from other uses that could have resulted in a return on that money.
5. The ability to recover prior milestone payments may be limited in the event of non-performance by the contractor.

Often with large aerospace programs, the end customer will incrementally fund the prime contractor, which creates an incentive for the prime contractor to incrementally fund subcontractors. If awarding a FFP subcontract with milestone payments, the subcontract should contain severable milestones that can be authorized and paid against as the prime contractor receives funding from its customer. It is important to remember that the terms of the subcontract contain the entire agreement between the prime contractor and their subcontractor. The subcontractor does not have insight into the status of the prime contract funding situation and therefore should not be expected to understand risks associated with performing tasks that have not been appropriately funded at the prime level. If the prime contractor authorizes the subcontractor to work on a task or milestone, then the prime contractor is responsible for paying the subcontractor for completion of those services regardless of whether the end customer ever funds the prime contractor.

Time-and-Material (T&M) contracts—Under this method of contracting, the parties negotiate clearly defined labor categories, to include minimum qualifications, and a negotiated fixed hourly billing rate for each labor category. T&M contracts are the least preferred method of contracting since they offer no incentive to the supplier to work efficiently. The supplier is paid the negotiated hourly rate for every hour worked. In addition to paying the supplier for labor hours, they are entitled to reimbursement of actual costs for all material, travel and other direct costs. Because of this, T&M contracts are the hardest to manage from a cost perspective, but are most appropriate for support services that cannot be well defined in terms of level of effort and requirements at the beginning of a contract. T&M contracting is used in both commercial and U.S. Government procurements.

Cost-Plus-Fixed-Fee (CPFF) contracts—This method is most commonly used with research and development type requirements where there are many known unknowns. Although the initial fixed fee is negotiated based on a percentage of the total estimated contract value, at the time of award it is awarded as a dollar amount. This provides some incentive for the subcontractor to work efficiently as they will be reimbursed for

actual costs incurred (as long as they are reasonable, allowable, and allocable as defined in the FARs for the U.S. Government contracts) but will only receive the fixed fee negotiated at time of subcontract award (unless scope is increased). If the subcontractor does not complete the work within the original estimated budget, the buyer may decide to either end the subcontract or increase the value of the subcontract to continue the work, but the subcontractor does not receive any additional fee, resulting in the effect of a diminishing profit rate to the subcontractor. CPFF type contracting is not typically used in commercial contracting. It is a contract type that is clearly defined in the FARs and requires that the recipient have adequate business systems to segregate costs by direct projects (individual contracts, task orders, grants), indirect costs, and unallowable or unbillable costs.

Cost-No-Fee (CNF) contracts—This method is most commonly used when awarding to an educational institution. Under this type of agreement, the educational institution is paid for all costs incurred that are considered reasonable, allowable and allocable to the project, up to the maximum ceiling value of the agreement, however, they are not be paid a fee or profit.

Incentive contracts—Incentive contracts can be either fixed-price or cost-reimbursement type contracts. FAR Part 16.4 prescribes the use of incentive contracts when

> …the required supplies or services can be acquired at lower costs and, in certain instances, with improved delivery or technical performance, by relating the amount of profit or fee payable under the contract to the contractor's performance. Incentive contracts are designed to obtain specific acquisition objectives by
>
> 1. Establishing reasonable and attainable targets that are clearly communicated to the contractor; and
> 2. Including appropriate incentive arrangements designed to
>   a. Motivate contractor efforts that might not otherwise be emphasized; and
>   b. Discourage contractor inefficiency and waste.

Level-of-Effort (LOE) contracts—Both Fixed-Price and Cost-Plus-Fixed-Fee contracts can be negotiated on an LOE basis. This method is typically used when the work to be performed can only be stated in general terms such as a study in a specified research area and where the deliverable is a report showing the results achieved through expending the required level of effort. LOE contracts must establish a required level of effort in the SOW, and contain a formula for calculating the reduction in price or fixed-fee if the total estimated hours are not provided.

Holding Contractors Accountable

Throughout the lifecycle of a subcontract or purchase order, both the Technical Representative (TR) and Procurement Representative will be responsible for monitoring the contractor's performance and their compliance with contract requirements. A surveillance plan that identifies the critical work processes, delivery schedule, deliverables, costs, etc., should be established and incorporated into the subcontract.

Whenever there is indication that a contractor's performance is below expectations, it should be addressed immediately, which gives the contractor reasonable notification

and sufficient opportunity to correct the shortcoming. Overlooking early warning signs can be detrimental to your project and limit the remedies available to the buying organization. Open and frequent communication among the TR, Procurement Representative, and subcontractor is the key to success. In order to monitor the subcontractor's performance both technical and fiscal reports should be reviewed in a timely manner by the TR and Procurement Representative and follow up discussions should occur with the subcontractor if problems are identified. It may also be advisable to build periodic program reviews with each subcontractor into the schedule to ensure that work progresses as planned. When a deliverable is received, it is the responsibility of the TR to promptly inspect the deliverable and determine if it meets contract requirements. If a deliverable does not meet contract requirements, the TR should immediately notify the Procurement Representative in writing, identify the deficiency, and state whether a variance is appropriate or if corrective action is necessary. The Procurement Representative should then work with the TR to communicate this information to the subcontractor. Ignoring deficiencies can lead to bigger problems down the road such as a perceived acceptance or waiver of contract rights, or standing up another supplier that can meet requirements or minimize disruption to the program.

Management Reserves

In large NASA aerospace programs, it is customary to account for the known unknowns by setting aside or reserving a sum of money (typically a percentage of the total estimated cost) for control purposes, both at the prime contract level as well as subcontracts for Science Investigation Teams. These monies are usually included in the total contract budget, but are not funded or authorized to be used without prior approval. Management Reserves (MR) are to be used when programmatic and technical risks are realized and opportunities are identified for work within the contract scope; they are not to cover out of scope work. The PjM should keep a log of MR debits and credits for traceability.

Examples of proper use of MR (either as a credit or debit) include, but are not limited to the following:

- Once work begins, one or more unplanned tasks are identified as necessary in order to complete the SOW.
- Rework, redesign, retest activities.
- Risk reduction/mitigation.
- Make/buy adjustments.
- SOW realignment between two organizations.
- Significant adjustments to indirect rates.

While it is recommended that MR be held at the project level—not embedded within the subcontract, there are instances when the Project Manager may elect to place the MR on the subcontract for visibility purposes. In those instances, MR should be tracked as a separate contract line item number (CLIN) in the subcontract and subcontract modifications should be issued to move reserve to the funding line when it is authorized. A MR Administration Plan should be developed at the onset of a program and communicated in writing to all

effected so as to establish clear procedures for the authorization and use of MR. This will help avoid confusion and conflict later.

A more thorough discussion of Management Reserve can be found in the Earned Value Management section of this handbook.

Understanding the Contract Modification Process for Prime and Subcontracts

Throughout the life of a prime or subcontract, the possibility exists that a change to the contract will be necessary, in order to increase or decrease scope, change schedule or period of performance, or modify any of the terms of a contract. The authority to modify a contract is typically defined in the contract. Under U.S. Government contracts, for instance, only the CO acting within the scope of their authority can modify the contract. Similarly the subcontract terms typically define the Contractual Point of Contact as the only representative authorized make changes to the scope of work, cost or time required for contract performance or the terms and conditions of the contract. For simplicity sake the representative authorized to modify a contract or subcontract, whether discussing the U.S. Government, prime contractor, or subcontractor, will be referred to as the Procurement Representative.

When a contractor believes that the customer has effected or may effect a change in the contract that has not been approved in writing and signed by the Procurement Representative, the contractor, working through their authorized TR, should notify the Procurement Representative in writing as soon as possible. This will allow the Procurement Representative to evaluate the alleged change and either confirm the change and direct the mode of further performance, countermand the alleged change, or notify the contractor that no change is considered to have occurred.

Understanding Termination Clauses of a Contract

There are two types of termination clauses, termination for convenience or termination for default. In addition, contracts can be terminated in whole or in part. The contract terms define the rights and responsibilities of the parties under each scenario and should provide for the settlement of costs and fee, if any.

Under a termination for convenience the buyer (customer) has the right to terminate the contract or subcontract without cause. This right is typically exercised when there is a change in direction of the program, funds are no longer available to pay for the continuation of the program, or when it is in the best interest of the buyer. The contractor's rights to recover costs are dictated by the termination language of the contract and can vary based on whether the contract type is fixed-price or cost-reimbursable. Under a termination for convenience, the contractor is generally compensated fairly for the work done and the preparations made for the terminated portion of the contract.

A termination for default, on the other hand, is exercised because of the contractor's actual or anticipated failure to perform its contractual obligations. Contract terms should include specific steps that need to be taken in order to give the contractor the opportunity to correct the default prior to a termination.

U.S. Export Control Laws

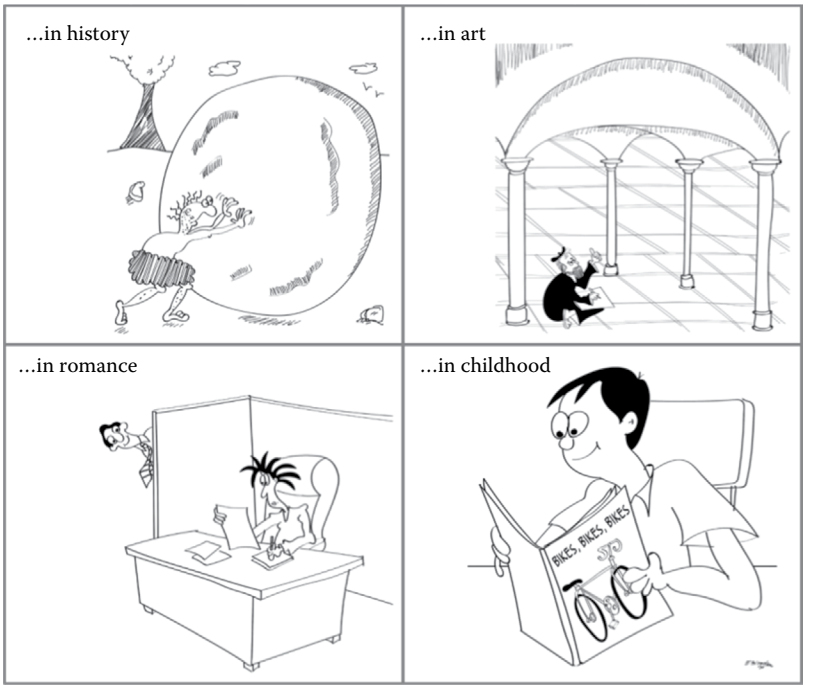
Whenever working with or for non-U.S. persons, foreign governments or foreign organizations, whether in the United State or abroad, it is important to take into consideration U.S. Export Control Laws. Statements of work should be reviewed by an export control SME to determine if an Export License or Technical Assistance Agreement is needed prior to entering into agreements or contracts, and certainly prior to sharing of technical data. U.S. Export Control Laws are complicated and require a full understanding of International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR). Violations of Export Control Laws can result in significant fines and imprisonment and can impact not only an organization but also individuals within that organization.


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Section II

Aerospace Project Process and Control Topics

Project Management—Phase A (Preliminary Analysis)




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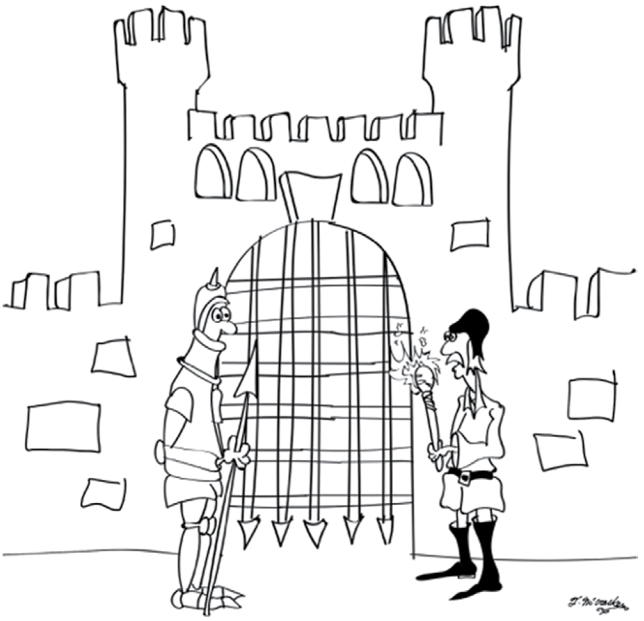
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Aerospace Mission Assurance

Steven J. Pereira

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IT'S THE SEASON FOR PILLAGING.
BEST INSPECT THIS WEEKLY

> For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.
>
> **—Richard P. Feynman [1]**

Introduction

To increase the likelihood of mission success within the defense and aerospace community, and specifically within the space systems development community, various best practices, recommendations, and requirements related to safety, quality, and mission assurance have developed over time. Many of these practices, recommendations, and requirements are traceable to specific accidents, mishaps, quality escapes, problems, and failures that have occurred during mission development. Because of this experience-based body of guidelines, space system development organizations often expend significant resources to develop and maintain their safety, quality, and mission assurance organizations and associated processes [2]. Safety and mission assurance programs are implemented by organizations developing space systems for a variety of reasons, including the following:

1. The customer (or sponsor) may contractually require the implementation of such a program based on the nature of the work, especially if the development cost is significant or the consequences of accidents or failures are severe.
2. The policies of the development organization may mandate implementing such a program, especially if the effects of accidents or failures are serious or if the organization is committed to and holds itself accountable for delivering systems that meet contract requirements and are fit for their intended use.
3. The project team believes that implementing such a program will have a positive return on investment and help guide the project toward success.

There is no single safety and mission assurance approach that is appropriate or optimal for every aerospace system. Safety and mission assurance approaches need to be tailored, given the nature of the project, the risk tolerance of the Sponsor, and the risk tolerance of the development organization. Both NASA Procedural Requirement 8705.4, "Risk Classification for NASA Payloads" [3] and DOD-HDBK-343, "Design, Construction, and Testing Requirements for One Of A Kind Space Equipment" [4] provide example risk based classifications for space missions. The Aerospace Corporation's Technical Operating Report TOR- 2011(8591)-21, "Mission Assurance Guidelines for A-D Mission Risk Classes" [5] provides example tailoring of mission assurance requirements for various mission risk classifications. When properly scoped, safety and mission assurance programs assist the project manager in maintaining control over a project by foreseeing upcoming challenges, risks, and problems before they are realized while guiding the project toward success.

Role of Safety and Mission Assurance in Aerospace Project Management

The safety and mission assurance program is an interdisciplinary effort, typically drawing on the skills of various functional specialists. The safety and mission assurance program is led by a designated individual (sometimes called a Systems Assurance

Manager [SAM], a Mission Assurance Manager [MAM], or a Chief Safety and Mission Assurance Officer [CSO]) that supports the project manager and reports independently to the development organization's upper management. Just as the Mission Systems Engineer advises the project manager on the technical status of the effort, the SAM advises the project manager on emergent safety and mission assurance issues. In some organizations, the SAM (and the overall mission assurance effort) operates fully independently of the project, with no reporting path to the project manager. This maximizes the independence of the assurance effort, but often comes at the expense of overall efficiency. In high-performing, mature organizations, the SAM (and the overall mission assurance effort) can be integrated with the project with an independent reporting path to upper management. Although the SAM has an independent reporting path, it is necessary for the SAM and everyone else involved in the mission assurance effort to feel they have a stake in steering the project toward success. For a space system, overall mission success includes

- Successfully assembling, integrating, and testing the spacecraft and its payload(s)
- Successfully delivering the spacecraft and its payload(s) to the launch site
- Successfully conducting launch site operations
- Successfully launching the spacecraft into space
- Successfully meeting operational/performance requirements for the required mission duration while completing the mission on-time and within budget

Throughout the project life cycle, the SAM performs a variety of roles. At project inception, the SAM establishes the safety and mission assurance requirements for the project, carefully balancing the nature of the project with the risk tolerance of the Sponsor and the development organization, as well as cost and schedule constraints. In this role, the SAM acts in a legislative role, proposing a rule set that must also be acceptable to the project manager. These requirements are baselined and documented in accordance with project configuration management requirements. As project development proceeds, the SAM is often charged with performing a policing function to ensure the established assurance requirements are being followed. This includes the critical function of evaluating and processing exceptions to technical requirements and safety and mission assurance requirements, ensuring adequate technical rationale is provided to justify the exception and guarantee any residual risk associated with the exception is properly characterized. Additionally, the SAM independently assesses project activities for the project manager and the development organization's top management. In this role, the SAM acts as a weatherperson on the local news, independently reporting current conditions and forecasting potential challenges. As problems and failures occur, the SAM serves the role of investigative reporter, ensuring that the root cause is identified and that corrective action is implemented to prevent recurrence. The SAM is also a collaborator, drawing upon deep subject matter expertise to help the development team find solutions to problems, failures, and other challenges that arise. Given the independent reporting chain of the SAM, this individual can also take on a role similar to a counselor, openly listening to project staff that are unable or unwilling to raise concerns directly with technical leads or the project manager. Since the project team can quickly become fixated on project cost or schedule constraints, the SAM often needs to be an outspoken proponent of quality and safety, helping to ensure the project team focuses on mission assurance throughout the project's life cycle.

Disciplines within the Safety and Mission Assurance Functional Area

While organizational structures and constructs vary across the industry, in general, the SAM leads a team that focuses on the following core disciplines:

1. Hardware Quality Assurance
2. Software Quality Assurance
3. Supplier Management
4. System Safety

Hardware Quality Assurance and Software Quality Assurance focus on activities to ensure the quality of the end items being designed, developed, fabricated, assembled, integrated, and tested or otherwise used by the aerospace system. These areas are functionally similar in their focus on both products and the processes used to develop products for use in an aerospace system. Supplier Management includes the activities of qualifying and managing suppliers and verifying that the supplied product meets the project requirements. System safety ensures that hazards associated with the system under development are mitigated to acceptable levels and that the system and any fabrication, assembly, integration, and test operations are conducted in accordance with applicable safety requirements. The system safety effort also ensures that the system is developed to meet the requirements of the appropriate launch range and that hazards to the public, range personnel, and range infrastructure are mitigated to acceptable levels.

Table 6.1 summarizes the key disciplines that support the overall safety and mission assurance program. The table provides a brief description of what is done by each discipline and why it is relevant to the overall safety and mission assurance program. Given the broad nature of these disciplines, it is impractical to address them in detail in this chapter. However, references are provided for further reading. For the mission assurance practitioner, the "Mission Assurance Guide," edited by S. B. Guarro and W. F. Tosney and published as The Aerospace Corporation's Technical Operating Report TOR-2007(8546)-6018 Revision A [6] provides a comprehensive review of the various mission assurance disciplines and the integration of mission assurance functions. Retrospective summaries of effective safety and mission assurance program can also be consulted [7].

Product and Process Assurance Approaches

The approaches used to implement assurance activities can be categorized as product oriented, process oriented, or a mixture of both. Product-oriented approaches typically focus on test, measurement, and inspection to verify quality. Process-oriented approaches tend to focus on developing and implementing repeatable processes to ensure the output of the process is conforming to applicable requirements [8]. For noncritical items used in aerospace systems, product-oriented quality approaches that inspect and verify the quality of the end-item can be adequate. Items that are either critical or complex merit an increased focus on both product and process assurance methods, such as SAE AS9003.

TABLE 6.1

Key Disciplines/Activities That Support the Safety and Mission Assurance Program

Discipline	What Is Done	Why Is It Done	References for Further Reading
Configuration management	Configuration management planning Configuration identification Change control Configuration status accounting Configuration audit Establishment of baselines and management of changes to baselines	To ensure consistency between product's performance, functional, and physical attributes with its requirements, design and operational information throughout its life	SAE ANSI/EIA-649B, "National Consensus Standard for Configuration Management" SMC-S-002, "Configuration Management"
Contamination control	Establishment of a contamination budget and implementation of controls to assure required levels of cleanliness are achieved and maintained	To protect sensitive items from damage from molecular or particulate contaminants	IEST-STD-CC1246E, "Product Cleanliness Levels—Applications, Requirements, and Determination"
Reliability engineering	Evaluation of design alternatives, trade studies, and designs, and verification of design implementations against mission lifetime and fault tolerance requirements	To verify the robustness of designs; demonstrate compliance with fault tolerance requirements	NASA-STD-8729.1, "Planning, Developing and Managing an Effective Reliability and Maintainability (R&M) Program" NASA Reference Publication 1358, "System Engineering 'Toolbox' for Design-Oriented Engineers" SMC-S-013, "Reliability Program for Space Systems"
Manufacturing engineering	Review the design against the capability of machines and people involved in manufacturing and assembly operations	To ensure that the design is capable of being successfully manufactured	SAE AS9100C, "Quality Management Systems—Requirements for Aviation, Space, and Defense Organizations"
Technical review	Independently evaluate designs and implementations consistent with life cycle stage	To ensure that the design meets or exceeds project requirements	NPR 7123.1B, "NASA Systems Engineering Processes and Requirements" SMC-S-21, "Technical Reviews & Audits for Systems, Equipment and Computer Software"
Government Industry Data Exchange Program (GIDEP)	Review parts and materials lists against Alerts and Advisories	To ensure that products with known or suspect reliability are not incorporated into flight articles	GIDEP Operations Manual

(*Continued*)

TABLE 6.1 (*Continued*)

Key Disciplines/Activities That Support the Safety and Mission Assurance Program

Discipline	What Is Done	Why Is It Done	References for Further Reading
Parts, materials, and processes	Detailed review of every part and material used in a flight system	To ensure parts, materials, and processes used in the design are compatible with the environment and screened, qualified, and derated in accordance with mission lifetime expectations and meet specified requirements	EEE-INST-002, "Instructions for EEE Parts Selection, Screening, Qualification, and Derating" MSFC-STD-3012, "EEE Parts Management and Control Requirements for MSFC Space Flight Hardware" NASA-STD-6016, "Standard Materials and Processes Requirement for Spacecraft" MSFC-STD-3029, "Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments" NASA RP-1124, Rev. 3 "Outgassing Data for Selecting Spacecraft Materials" SMC-S-009, "Parts, Materials, & Processes Control Program for Space and Launch Vehicles" SMC-S-010, "Technical Requirements for Electronic Parts, Materials, and Processes For Space and Launch Vehicles" SMC-S-011, "Parts, Materials, and Processes Control Program for Expendable Launch Vehicles"
Risk management	Evaluate the likelihood and severity of threats to mission success before they are realized in a closed loop tracking system	To systematically evaluate threats to project success before they occur and take proactive action to mitigate them	NPR 8000.4A, "Agency Risk Management Procedural Requirements" NASA/SP-2011-3422, "NASA Risk Management Handbook" ISO/DIS 17666, "Space Systems—Risk Management"
Occupational safety and health	Comply with local, state, and national safety and health regulations	To ensure that people are protected from hazards associated with manufacturing, assembly, integration, and test	29 CFR 1910, "Occupational Safety and Health Standards" DOD 4145.26-M, "DOD Contractor's Safety Manual For Ammunition and Explosives"

(*Continued*)

TABLE 6.1 (*Continued*)

Key Disciplines/Activities That Support the Safety and Mission Assurance Program

Discipline	What Is Done	Why Is It Done	References for Further Reading
Range safety	Evaluate designs against applicable range safety design criteria	To ensure risks to public, range personnel, and range facilities are adequately mitigated in accordance with established criteria	AFSPCMAN 91-710, "Range Safety User Requirements Manual" NPR 8715.7A, "Expendable Launch Vehicle (ELV) Payload Safety Program"
Nonconformance review and disposition	Closed loop tracking of nonconformances with containment, root cause analysis, corrective action implementation, and corrective action verification	To ensure nonconformances are not repeated by finding root cause and implementing corrective action to prevent recurrence	SAE AS9100C, "Quality Management Systems—Requirements for Aviation, Space, and Defense Organizations"
Electrostatic Discharge (ESD) control	Implement an ESD control program	To ensure hardware is safeguarded from ESD risk during all operations	ANSI ESDS S20.20, "Standard for the Development of an Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)"
Design qualification	Qualification, acceptance, and/or protoflight testing in environments	To ensure the design is robust in all predicted environments (transportation, launch, operational environment)	GSFC-STD-7000A, "General Environmental Verification Standard" MIL-STD-1540D, "Product Verification Requirements for, Launch, Upper Stage, and Space Vehicles" SMC Standard SMC-S-016, "Test Requirements for Launch, Upper-Stage, and Space Vehicles"
Metrology and calibration	Calibration of measurement equipment in accordance with approved processes and standards traceable to NIST	To ensure the accuracy and precision of measurements	ANSI/NCSL Z540.1, "Calibration Laboratories and Measuring and Test Equipment—General Requirements" ANSI/NCSL Z540.3, "General Requirements for the Competence of Testing and Calibration Laboratories" ISO 17025, "General Requirements for the Competence of Testing and Calibration Laboratories"

(*Continued*)

TABLE 6.1 (*Continued*)

Key Disciplines/Activities That Support the Safety and Mission Assurance Program

Discipline	What Is Done	Why Is It Done	References for Further Reading
Planetary protection	Classify mission in accordance with planetary protection categories and implement applicable requirements	To ensure avoidance of the biological contamination of extraterrestrial environments and ensure precautions are taken to protect Earth's from extraterrestrial matter	NPD 8020.7G, "Biological Contamination Control for Outbound and Inbound Planetary Spacecraft" NPR 8020.12D, "Planetary Protection Provisions for Robotic Extraterrestrial Missions"
Orbital debris	Preparation of Orbital Debris Assessments and End Of Mission Plans	To ensure compliance with federal policies and requirements to minimize the potential to generate orbital debris during deployment, mission operations, and after the mission has been terminated	NASA-STD-8719.14A, "Process for Limiting Orbital Debris"
Corrective and preventive action	Closed-loop tracking of process and product escapes with containment, root cause analysis, corrective action implementation, and corrective action verification	To ensure process and product escapes are not repeated and that overall performances continuously improves over time	SAE AS9100C, "Quality Management Systems—Requirements for Aviation, Space, and Defense Organizations"
Lessons learned	Collection, distribution, and periodic review of lessons learned from work activities	To enable organizational improvement over time	NASA Lessons Learned Information System (http://llis.nasa.gov/) DOE-HDBK-7502-95, "Implementing U.S. Department of Energy Lessons Learned Programs" U.S. Space Program Mission Assurance Improvement Workshop Collaboration on Quality in the Space and Defense Industries Forum

Work that is critical and complex is best suited for an assurance approach that involves both product and process assurance, such as SAE AS9100. NASA Policy Directive (NPD) 8730.5B, "NASA Quality Assurance Program Policy" [9] provides guidelines for how work can be classified as either critical or not critical and complex or not complex. Both product- and process-orientated methods rely on auditing, or sampling, to verify conformance to established requirements. Nonconformances identified by audit should be tracked to closure by the safety and mission assurance organization. Closure of nonconformances should require containment, root cause analysis, and corrective action implementation to prevent recurrence.

Role of Developer versus Role of Acquirer for Safety and Mission Assurance

In the development of aerospace systems, the developer and the acquirer (sometimes referred to as the sponsor or customer) tend to have different roles and responsibilities with respect to safety and mission assurance. The project manager of an aerospace system should understand these differences so that they can appreciate the perspectives of the individuals performing these functions. While roles and responsibilities will vary, in general, the acquirer's safety and mission assurance effort is responsible for specifying and approving the top level requirements for mission/project, including driving safety and mission assurance requirements, and providing independent technical surveillance depending on the agreement with the developer. In some cases, the acquiring safety and mission assurance organization will have oversight of the developer's activities; in other cases, the acquirer will only have insight over the developer's activities. The developer's safety and mission assurance effort is responsible for establishing the top level requirements and implementing processes in compliance with those specified by the acquirer. The developer's safety and mission assurance effort is also responsible for developing subordinate safety and mission assurance related requirements, implementing procedures to ensure that development occurs in compliance with applicable requirements, and providing oversight of all development activities. Since this book is focused on project managers leading aerospace development efforts, the remainder of this chapter focuses on developer safety and mission assurance activities.

Safety and Mission Assurance during Project Life cycle Phases

As stated earlier in this chapter, during project formulation, the initial task of the safety and mission assurance team is to establish and baseline the project-specific safety and mission assurance requirements. Table 6.2 shows the typical activities of the safety and mission assurance team supporting the development of an aerospace system starting in the preliminary design phase. This table was prepared using the NASA definitions of project life cycles, but is extensible and can be easily adapted to and aligned with other life cycle models.

TABLE 6.2

Typical Safety and Mission Assurance Activities during Life Cycle Phases B–E

Role	Phase B: Preliminary Design and Technology Completion	Phase C: Final Design and Fabrication	Phase D: System Assembly; Integration and Test; Launch and Checkout	Phase E: Operations, Sustainment, Closeout
Systems assurance manager	Finalize safety and mission assurance plans and requirements Ensure flowdown of Project safety and mission assurance requirements to subcontractors Identify risks and provide independent risk assessment for all project risks Coordinate activities of the safety and mission assurance team Ensure project execution is in compliance with project plans Coordinate SMA inputs to inheritance reviews and subsystem Preliminary Design Reviews (PDRs) Present safety and mission assurance status at Project PDR	Identify risks and provide independent risk assessment for all project risks Coordinate activities of the safety and mission assurance team Review environmental test plans and reports Review Orbital Debris Assessment report Perform independent review of reliability analyses Assess problem/failure reports for residual risk Review and approve final parts lists for pedigree and radiation performance Review and approve flight drawings, test plan, and test procedures Assess GIDEP and Sponsor alerts Ensure project execution is in compliance with project plans Coordinate safety and mission assurance inputs to subsystem CDRs Present safety and mission assurance status at Project Critical Design Review (CDR) and System Integration Review Assess any waivers for residual risk	Identify safety and mission assurance risks and provide independent risk assessment for all project risks Coordinate closure of residual actions from analysis, parts list reviews, inspection reports, anomaly reports, and waivers Review system/environmental test plans and reports Review updated reliability analysis as necessary and close out analysis action items Assess problem/failure reports for residual risk Review and approve final parts lists for pedigree and radiation performance Perform Physical and Functional Configuration Audits Assemble End-Item Data Package Assess GIDEP and Sponsor alerts Ensure project execution is in compliance with project plans Present safety and mission assurance status at flight system Pre-Ship Review, Safety and Mission Success Review, and Project pre-launch reviews Assist preparation for Certification of Flight Readiness review (COFR) Participate in Operational Readiness Tests Ensure appropriate operational training for ops team Gather and document lessons-learned from safety and mission assurance team Assess any waivers for residual risk	Provide support for software updates and anomaly investigation Assess project's operational readiness for nominal and contingency scenarios Coordinate software assurance support Ensure project execution is in compliance with project plans Assess any waivers for residual risk

(*Continued*)

TABLE 6.2 (*Continued*)

Typical Safety and Mission Assurance Activities during Life Cycle Phases B–E

Role	Phase B: Preliminary Design and Technology Completion	Phase C: Final Design and Fabrication	Phase D: System Assembly; Integration and Test; Launch and Checkout	Phase E: Operations, Sustainment, Closeout
Hardware quality engineer	Perform supplier surveys Ensure suppliers are selected from Approved Supplier List	Ensure certification of personnel for handling or test of flight hardware Perform in-process inspections Review and approve QA nonconformance reports Review new technology packaging and assess need for packaging qualification Perform surveillance of suppliers	Perform in-process and final inspections Review and approve QA nonconformance reports Review End Item Data Package Support hardware delivery reviews Provide System Integration and Test support Perform surveillance of suppliers	
Software assurance engineer	Review and approve software classifications Review and assess Project and contractor Software Development Plans to assure compliance to project-specific Software Development Plan	Perform software process and product evaluations Assess software problem/failure reports Review traceability of software test to requirements	Perform software process and product evaluations Assess software problem/failure reports Support software delivery reviews Track open software delivery review items and approve software release notes	Provide support for software updates and anomaly investigation
System safety	Finalize Project Safety Plan Finalize Project Mishap Plan Conduct Range Safety introduction briefing Generate Safety Data Package (SDP) #1 (Missile Systems Prelaunch Safety Package)	Perform operations and facility safety surveys Review or generate safety mishap reports Perform hazard analysis Witness hazardous operations Generate SDP #2	Perform pre-environmental test and transportation surveys Review or generate safety mishap reports Witness hazardous operations Support launch campaign and range safety activities Generate SDP #3	
Configuration management	Configuration Management Plan Product Structure Document/drawing release	Document/drawing release Conduct Change Control Boards (CCBs)	Drawing/document release Conduct CCBs Physical configuration audit Functional configuration audit End Item Data Package preparation	Conduct CCBs
Supplier management	Conduct supplier risk evaluations	Perform pre-cap and source inspections Issue Supplier Corrective Action Requests as appropriate	Perform pre-cap, source inspections, and Mandatory Inspections Issue Supplier Corrective Action Requests as appropriate	

NASA project life cycle phases are described in NPR 7120.5E, "NASA Space Flight Program and Project Management Requirements w/Changes 1-15" [10] and NPR 7123.1B, "NASA Systems Engineering Processes and Requirements" [11].

Safety and Mission Assurance Requirements Flow Down

Given the complex nature of aerospace systems that often require specialized designs, component subcontractors and suppliers typically play a fundamental role in designing, developing, fabricating, integrating, and testing critical items. It is, therefore, imperative to select subcontractors and suppliers that have the capability and capacity to provide deliverables that meet project requirements. Many organizations implement a supplier risk evaluation process or supplier approval process to evaluate the technical capabilities, internal processes, and infrastructure of candidate suppliers in advance of any procurement in order to prequalify the supplier as an eligible source of supply.

The establishment, flow down, and management of safety and mission assurance requirements from the lead developer (or prime contractor) to subcontractors and suppliers is of critical import. For subcontracted items, the lead developer often prepares a specific safety and mission assurance requirements document customized for each subcontract that is invoked via either the subcontract statement of work or the technical specification. These customized safety and mission assurance requirements documents extract and invoke the applicable safety and mission assurance requirements from the project's baselined requirement set. For purchase orders of standard commodities, rather than having a stand-alone safety and mission assurance requirements document, many organizations have established standardized safety and mission assurance requirements that are invoked on each order.

Once the subcontract or procurement has been issued, the developer should implement surveillance over the subcontractor or supplier's work activities, consistent with the criticality of the procurement and the terms and conditions of the order or subcontract. For noncritical procurements, surveillance (in the form of insight) may take the form of status reporting from the supplier. For critical procurements, surveillance (in the form of oversight) may entail the deployment of staff from the lead developer's organization to the supplier and the imposition of mandatory independent inspections at the supplier's facility.

For critical procurements, it is often advisable to hold a kick-off meeting between the lead developer and the supplier to ensure the supplier fully understands the requirements of the order and the criticality of the work. Prior to the shipment of the product to the lead developer, a Pre-Ship Review is held, and the as-built product is verified to be compliant with the invoked requirements. Any nonconformances need to be resolved prior to acceptance.

In an effort to mature the technical capabilities of the supplier base and to prevent the recurrence of nonconformances on future projects, the lead developer may issue supplier corrective action requests to subcontractors and suppliers to ensure that process escapes that occurred while fulfilling the order are corrected. In order to be effective, the supplier corrective action request process must have linkages to both the supplier evaluation process and the overall procurement process to ensure that nonresponsive suppliers are removed from the list of suppliers eligible for future orders.

Safety and Mission Assurance Trends

Several trends have emerged in the aerospace safety and mission assurance domain over the past 10–15 years. These trends include

1. General growth in the volume of safety and mission assurance requirements being invoked on many aerospace systems
2. Sharp decline in the number of safety and mission assurance requirements cited on "low cost/high risk" programs
3. Realization of counterfeit parts risk
4. Increased focus on outsourcing critical items and components

These trends are discussed in the following paragraphs.

As organizations have sought to avoid repeating their mistakes (or the mistakes of others [12]), in many instances there has been a growth in the number of safety and mission assurance requirements being invoked on complex aerospace systems. Often, the corrective action for a nonconformance or failure is the development of a new rule that, if implemented, will prevent recurrence of that particular problem. This approach can become unmanageable (and even produce conflicting requirements) if not strictly managed. Additionally, for systems developed for the federal government, the acquisition reforms of the 1990s resulted in the retirement of many military standards. Some standards were replaced by commercial equivalents, but others were simply retired and have been replaced by a patchwork of similar, but slightly different, federal agency unique safety and mission assurance requirements.

At the federal level, as threats of government shutdown turn from rare occurrences into more frequent events, it has become challenging to plan effectively and execute multiyear development programs. Additionally, the promised economies of small satellites, CubeSats, and hosted payloads have helped to set expectations that space systems can be developed on a "shoestring" budget, which may be possible but often comes with compromises [13]. In this cost-constrained environment it is not unheard of for a customer to impose few, if any, safety and mission assurance requirements. One way the customer communicates their risk tolerance to the developer is via the safety and mission assurance requirements that are invoked on the lead developer at contract award. At the beginning of a project it is important for the customer and developer to define and agree on measurable success criteria for the project, as well as to confirm that they share the same risk tolerance in achieving those success criteria.

In the past decade, as the worldwide economy has globalized, the threat of counterfeit parts has become a reality, requiring careful attention and detail. Faced with obsolescence issues on certain parts commodities and fueled by an increasing volume of electronic waste, advances in counterfeiting technology, the rise of non-OEM franchised parts brokers, and greed, the risk of counterfeit parts entering the supply chain can no longer be ignored. Counterfeit parts can pass electrical tests, are known to have infiltrated the domestic market, and are sometimes sold by resellers who are unaware that their product is not authentic. Counterfeit parts risk mitigation programs should be implemented to ensure the authenticity of parts used in critical aerospace systems. Guidelines for an effective counterfeit parts prevention program can be found in SAE AS5553A, "Fraudulent/Counterfeit Electronic Parts; Avoidance, Detection, Mitigation, and Disposition" and SAE AS6174A, "Counterfeit Materiel; Assuring Acquisition of Authentic and Conforming Materiel."

As stated earlier in this chapter, subcontractors and suppliers are playing an increasingly significant role in mission assurance. In part to incorporate the latest technological advances and in part to lower development costs, lead developers are often increasingly relying on suppliers to deliver systems that meet mission requirements. For example, the Boeing 787 was planned to increase the amount of outsourcing used to 70% from between 35%–50% on earlier aircraft [14]. Providing adequate oversight of suppliers has always been a critical component of any safety and mission assurance program and will continue to be so for the foreseeable future.

Summary and Conclusion

Due to the complexity of the systems and technology associated with aerospace systems, successfully managing aerospace development projects can be exceptionally difficult. There are some canonical rules for project managers to consider [15,16]:

- Ensure test as you fly exceptions are understood and the risk is accepted for any variations.
- To the maximum extent possible, find the root cause of all failures. Failures that do not have the root cause identified cannot be credibly resolved to prevent recurrence.
- Track all nonconformances to closure and assess the residual risk of the totality of nonconformances. Sometimes the risk associated with the totality of nonconformances is greater than the sum of the individual risks.
- Pay attention to unexpected or out-of-family test results, as they are usually an indicator that something unexpected has changed in the design or the manufacturing process.
- Integrate the safety and mission assurance approach into the overall process of project management and engineering development. In many respects, aspects of the safety and mission assurance approach need to operate with independence from project management and engineering in order to be effective. However, the overall processes associated with safety and mission assurance need to be integrated with and accepted as part of the overall approach to project management and engineering development.

Safety and mission assurance programs are implemented to help ensure the developer is successful in meeting project requirements within the constraints of cost and schedule. The safety and mission assurance effort help the project manager maintain control over a project, foreseeing upcoming challenges, risks, and problems before they are realized while guiding the effort toward success. The safety and mission assurance team operates with independence to ensure that an unbiased assessment of project risks and status is reported to the project manager. There is no single safety and mission assurance approach that is appropriate or optimal for every single aerospace system. Safety and mission assurance approaches need to be tailored given the nature of the project, the risk tolerance of the customer (or sponsor), and the risk tolerance of the development organization.

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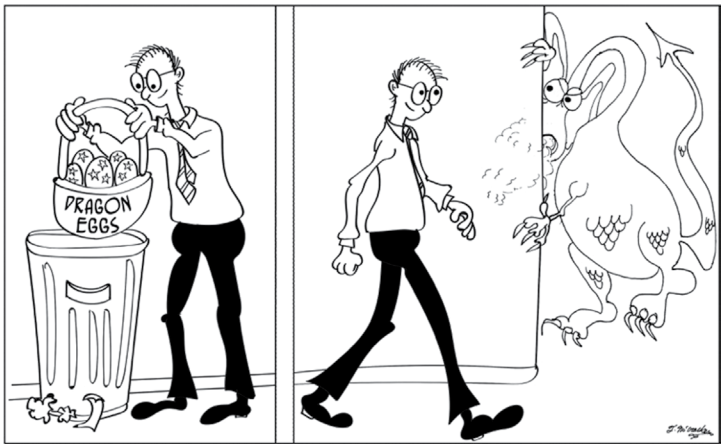
7

Risk Management

Kristin Fretz and Sanae Kubota

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GOOD RISK MANAGEMENT IDENTIFIES ISSUES EARLY

Introduction

Risk management (RM) is used by project managers to identify, evaluate, prioritize, and mitigate negative events before they become problems. Challenges and risks are not synonymous. Problems are defined as adverse events that have already occurred and must be dealt with (i.e., problems are risks that have come to fruition). In contrast, risks are potential problems that are managed in the hope of lowering the probability of occurrence. It is important for the program manager to not only understand what risk management is, but also how to perform and implement it. The intent of this chapter is to give project managers the background information on risk management along with the principles, methods, and tools to implement the appropriate risk management system/practice for their organization and project. Risk management is especially important on spaceflight missions where cost, schedule, and technical margins are tightly constrained.

At some level, informal risk management occurs on all projects and risk management is synonymous with project management. Project managers and engineering team members use their experience to anticipate problems and listen for signs of potential issues in meetings and discussions. However, this informal approach does not lend itself to communication and efficiency. A formal risk management system promotes teamwork by involving personnel at all levels of the project and helps the project team to understand the project's objectives, provides a rational basis for trades, and also provides a mechanism for achieving project goals. Additionally, a formal risk management program encourages the team to be forward thinkers who anticipate problems. Using a proactive approach to identifying problems early allows resources to be more efficiently allocated to these issues, and potential problems can be addressed when it is more cost-effective and simpler to do so (i.e., before they become crises). Most importantly, a risk management system encourages communication. By communicating potential problems to the team, the project manager ensures that the team is working toward a common goal; by communicating risks to the sponsor, the project manager ensures that uncertainties and concerns, and the potential mitigation or acceptance of those uncertainties and concerns, are known and understood.

Scope

Implementing a risk management system is not one-size-fits-all. A risk management system must be tailored to the needs of an individual project by selecting the methods and tools that best fit both the organization and project.

Though the fundamentals of risk management are the same for any project, there are some factors that determine the scope of the risk management system. First, the project size will determine to what extent to formalize risk management. For example, a less formal risk management approach led by the project manager may be sufficient for a simple, small CubeSat project, while a complex systems-of-systems project may require a risk management team. Scalability comes in the form of how many people are involved in the process, how much management reserve is available for mitigation plans, and, to some extent, which RM tool is used for documenting and capturing risk management process details.

A second factor influencing the scope of the risk management system is the level of participation for internal and external organizations and stakeholders. The project manager

must decide if internal or external project teams manage risks at their level and to what extent they need to be integrated into the overall project risk management process. If it is determined that a project needs risk boards at varying levels (typically at the element level, a discrete, but significant, well-defined product of the project such as a major subsystem or instrument), the project manager must provide guidance for when risks should be elevated to the project level. Typically, risks are elevated when project safety, technical performance, mission requirements, external interfaces, resources, or schedule are affected or when a risk may impact another element. Not all external organizations have a defined risk management system. In this case, the project manager must determine if it is necessary and feasible to use project resources to establish a formal risk management system for external suppliers or stakeholders.

Finally, a determination must be made concerning what does and does not belong in the risk management system so that there is a precise definition of what should be tracked in the formal system. Defining this allows the system to be effective; otherwise, significant time can be spent tracking and managing risks that are not worth maintaining or technical activities that represent challenging but expected work rather than a true risk.

Participant Roles

The membership of the risk board(s) is determined by the project manager or lead engineer of the institution providing the element/component, typically in conjunction with the sponsor or customer. Often the basic process and participation, including authorities for adjudicating risks, are established in contractual language or defined in a risk management plan as an early deliverable. It is critical for everyone involved in the risk management process to understand his or her role and to actively participate in risk management meetings. Without participation in the process, there is potential for miscommunication about a risk, the current status of that risk, and the actions needed to mitigate that risk. Table 7.1 summarizes the roles and responsibilities for those involved in the risk management process.

Types of Risk

A project risk is a scenario that jeopardizes the likelihood of project success and focuses on the areas of cost, schedule, technical, safety, or programmatics. Many risks will impact multiple areas. There is frequent overlap between cost and schedule risks, as many risks to maintaining schedule may be mitigated by spending more to add resources to a task. Likewise, technical risks can be reduced with additional personnel (cost) and time (schedule) to understand and resolve the issue. Risks are classified in the category that would be impacted most directly without mitigation.

- *Inherent to project concept*: All aerospace projects carry inherent risk. It is important to recognize early in the project life cycle those risks that are unique to the project concept and which will require particular focus beyond what is typically given to that area.

TABLE 7.1

Risk Management Roles and Responsibilities

Role	Responsibilities
Project Manager	• Owns the risk management process and the risks within the project • Sets the "tone" for the process • Chairs the risk management meetings and governs the assignment of personnel to risk boards • Assigns risk action (analyze, accept, close, mitigate) • Authorizes expenditures of resources for mitigation • Assigns/changes responsibility for risks and mitigation plans within the project • Reviews recommendations on approach and actions • Re-prioritizes all risks to determine top project risks • Reports risk status to the sponsor/stakeholders who are materially affected by the outcome of a decision or deliverable
Risk Manager	• This role is dependent on the size of the project • If the project has a dedicated risk manager, that person aids the project manager in the execution of the risk management process • Facilitates the meetings by developing the agenda, distributing risk reports to attendees in advance of the meeting, and distributing the meeting minutes afterward • Assists in the timely management of risk items • Maintains the risk management database • Updates status of open risks with risk assignees • Collects and reports general risk management measures/metrics
Project Senior Staff/ Systems Engineers	• Key participants in the risk process since they support the PM's decision making and the knowledge needed to evaluate risks • A subject matter expert in one or more areas • Evaluate potential risks • Evaluate alternatives and likely outcomes • Evaluate risks and mitigation plans
Subsystem Leads	• Evaluate potential risks • Review risk attribute (consequence and likelihood) • Define alternatives and likely outcomes • Recommend approach and actions • Support implementation of action plans • Responsible for risks attributed to their subsystems
All project personnel	• Identify potential risks (watch items) • Assist in assigning consequence and likelihood • Provide context information
Risk Assignee	• Develops impact analysis for specified risk • Defines alternatives and likely outcomes • Recommends approach and actions • Monitors risk and reports status of open risks • Takes responsibility for implementation and reports on status of mitigation plans
Suppliers	• Identify potential risks and report them to the project • Estimate risk attributes • Provide context information

Recognizing these risks communicates to both the sponsor(s) and the team that project management is aware of the uniqueness and provides a formal mechanism to determine the plan to mitigate and monitor the progress in reducing the risk.

- *Technical*: Technical risks jeopardize the performance capability of the project. The area in jeopardy might be maintaining sufficient on-orbit reliability, meeting performance specifications, or sufficient margin (e.g., power, mass, thermal,

propellant/delta-V capacity). The risks may stem from limitations in analytical capability, verification, and testing approaches, or new technology.

- *Cost/schedule*: Schedule risks manifest when estimated time to reach objectives is believed to be inaccurate. This may include late delivery of a component from a vendor, unexpected unavailability of required resources, or simply a potential change in schedule for external reasons. Contractual and budgetary constraints drive cost risks. Similar to schedule risks, they manifest when the estimated cost to reach objectives is believed to be inaccurate. Both cost and schedule risks may arise when there is a failure to identify and mitigate developmental or operational risks.
- *Safety*: Safety risks are those scenarios in which project activities (e.g., integration or test) may have a potential for injury to personnel or damage to facilities or project hardware.
- *Programmatic risk*: Programmatic risks involve the sponsor and subcontractor business relationships, legal actions, or other contractual issues.

Tools

The Team

The tool most important to many aspects of a successful project is an engaged and invested team, and risk management is no different. A project manager will depend on the team to provide insight into project status, to communicate as they become aware of risks to project success, and to lead or support efforts to manage the risks. This aspect of communication is critical; an engaged team effectively communicates unique potential challenges up the organization structure, to include the sponsor, and across the breadth of the technical team.

To most effectively engage team participation, it is vital for the project manager to effectively communicate what the goals of the risk management process are: how it will be implemented and how it will benefit the project. It should be made clear that risk identification is encouraged. This may include a tutorial on what funding or schedule reserve is held to address risks, how and when it may become available, and some examples to illustrate the challenges of wanting to buy down all risk while also needing to save for risks that will be uncovered in the future. In addition, an effective balance between a formal process to ensure communication and tracking, and the burden of maintaining a risk management process will encourage staff at all levels to bring forward candidate risks; if the process is too burdensome it discourage staff from communicating concerns, which can lead to problems that appear to occur all of a sudden.

Risk Meeting

Recurring meetings should be scheduled to take place at least once per month to ensure continuity in the process. Meeting frequency may vary throughout the project life cycle, with increased frequency during periods of increased activity. It is important to schedule meetings with high enough frequency to ensure risks are unlikely to arise and be realized without the opportunity to be brought to the risk board.

Goals of Meeting

Meetings should be structured such that all open risks are reviewed at an appropriate frequency (risks with higher risk scores may be evaluated at the higher frequency than those with lower risk scores, for example, but all should be regularly reviewed). The goal of the meetings should be to ensure that the current risk status is maintained for each risk, and any needs or concerns relevant to the ongoing mitigation step(s) are discussed.

Managing the Meeting

Risk meetings may be managed by either the project manager, a deputy project manager, or a dedicated risk manager. The risk owners should update the status of their risks before the meeting. This ensures that the session can focus on group discussion of the situation rather than spending the time dictating status input.

Risk Evaluation

Candidate risks are formally introduced at risk meetings; informal discussion before meetings is encouraged but not required. During the meeting, the risk board will ensure that there is agreement as to whether a candidate risk should be accepted and that the risk statement is properly constructed. It will then be assigned an initial risk score (based on likelihood of occurrence and consequence of realization), and a mitigation plan will be developed and documented.

Open risks are evaluated during the risk meeting. Status of the current mitigation step(s) and any potential updates to the mitigation plan are discussed. This is an opportunity for the risk owner to ensure that project management has an understanding of the situation and for project management to weigh whether or not additional resources or mitigation steps are warranted.

Mitigation Plans

The path forward for a project risk is laid out in its mitigation plan. The complexity and duration of the mitigation plan will vary; sometimes only one step need be considered and other times the mitigation plan may have a multitude of actions and span project phases. Regardless of the number of steps in the mitigation plan, each step must be assigned start and finish dates and the expected new risk score (likelihood and consequence) at its completion so that progress may be anticipated and tracked. A project manager may consider risk mitigation plans to project action items, and track them as they do other action items.

Risk Database

A risk management database should be created to maintain the risks. The risk management database does not need to be a sophisticated tool—depending on the needs of the project, a spreadsheet, database applications such as Microsoft Access or FileMakerPro, or COTS risk management software can be used.

TABLE 7.2

Risk Management Database Information

Data Field	Description
Identifier	Unique identifier name/number for the risk
Title	Brief name for the risk
Board action	Reflects the current action status of the risk (accept, close, elevate, reject)
Statement	Short written statement in condition and consequence (i.e., if–then format) that provides sufficient information to justify consequence and likelihood evaluations; evaluation should consider potential impact on all project elements
Context	Short, informal, written statement that provides sufficient information to describe how the risk could occur and the consequence of the risk should it occur
Likelihood	Probability value as defined in Table 7.3
Impact	Consequence value as defined in Table 7.4
Timeframe	The timescale in which a risk is a threat to the project: near-term (up to 3 months), mid-term (3–6 months), or long-term (6–12 months)
Area	Specific subset within the review board's scope
System/subsystem	Used to note specific component or area subset affected
Rank	Current priority number assigned by the risk board chair and project manager
Mitigation strategy	Realistic, measureable approach for mitigating the risk (including necessary resources); consists of an action plan intended to decrease the risk severity with the ultimate goal being to eliminate the potential for negative impact to the project
Originator	Person who initially identified the risk
Date identified	Date on which the risk was accepted into the risk management database
Risk owner	Person assigned to manage the risk
Risk action	Board action assigned to the risk: research, mitigate, watch
Classification	Safety, cost, schedule, technical, or unspecified
Status	Used to describe a change in status of an identified risk with explanation why the change was made

Independent of the software tool used to track risks, the risk database should include the information shown in Table 7.2.

Typically, the information needed for the risk database is obtained by surveying the team. The project manager and risk manager must discuss each risk with the originator to determine the context, likelihood, consequence, timeframe, mitigation, and so on. All of this information is needed to ensure the risk is understood and to write the risk statement appropriately. Typically, the risk statement uses an "if–then" construct, but any construct that includes a fact-based condition, followed by the worst-case consequence, can be utilized. Example: "If the launch vehicle and third stage combination cannot deliver the required launch energy for the baseline mission design mass; then mass margins may be reduced to an inadequate level."

Metrics

Risks are characterized in several ways. First, the likelihood of occurrence and the consequence of realization are assessed. Each is typically graded on a scale of 1–5, and the two are multiplied together to provide the risk's score or risk severity. Tables 7.3 and 7.4 are

TABLE 7.3

Risk Likelihood Criteria

Likelihood	Safety (Likelihood of Safety Event Occurrences)	Technical (Likelihood of not Meeting Mission Technical Performance Requirements)	Cost/Schedule (Likelihood of not Meeting Allocated Cost/Schedule Requirement or Margin)
5 Very high	($P_{SE} > 10^{-1}$)	($P_T > 50\%$)	($P_{CS} > 75\%$)
4 High	($10^{-2} < P_{SE} \leq 10^{-1}$)	($25\% < P_T \leq 50\%$)	($50\% < P_{CS} \leq 75\%$)
3 Moderate	($10^{-3} < P_{SE} \leq 10^{-2}$)	($15\% < P_T \leq 25\%$)	($25\% < P_{CS} \leq 50\%$)
2 Low	($10^{-6} < P_{SE} \leq 10^{-3}$)	($2\% < P_T \leq 15\%$)	($10\% < P_{CS} \leq 25\%$)
1 Very low	($P_{SE} \leq 10^{-6}$)	($P_T \leq 2\%$)	($P_{CS} \leq 10\%$)

TABLE 7.4

Risk Consequence Criteria

Level	Minimal (1)	Minor (2)	Medium (3)	Major (4)	Very High (5)
Safety	Negligible safety impact	Minor injury with no lost work time	Injury with lost work time	Severe injury	Death or permanent disabling injury
Technical	Negligible technical impact	Decrease in spacecraft or payload capability/margin, but all mission requirements met, or need for requirement definition or design/implementation workaround	Major loss of capability of spacecraft or payload	Loss of one or more mission-driving requirements	Loss of spacecraft, Instrument, or payload
Cost	Project cost overrun of less than 1% of allocated	Project cost overrun between 1% and 3% of allocated	Project cost overrun between 3% and 10% of allocated	Project cost overrun between 10% and 20% of allocated	Project cost overrun of greater than 20% of allocated
Schedule	Negligible schedule slip	Schedule slip not on critical path	Schedule slip affecting critical path but not launch or post-launch critical event	Schedule slip of 1–3 months	Schedule slip greater than 3 months

examples of standard definitions of the likelihood and consequence levels for safety, technical, cost, and schedule risks; these thresholds can be adjusted up or down according to the size and the risk posture of the project.

The risk scores are typically represented in a 5×5 matrix (example shown in Figure 7.1), with the highest risks in the upper right corner and the lowest risks in the lower left corner. In addition to ranking by risk score, risks are also often described by color: red risks are the most severe, green the least severe, and yellow are in the middle.

The metrics of scored and colored risks are used to communicate the current risk status of the project and may be tracked over time to provide trending insight to assess the effectiveness of mitigation plans.

Likelihood						
	Very High (5)	Green	Yellow	Red	Red	Red
	High (4)	Green	Yellow	Yellow	Red	Red
	Moderate (3)	Green	Yellow	Yellow	Yellow	Red
	Low (2)	Green	Green	Green	Yellow	Yellow
	Very Low (1)	Green	Green	Green	Green	Yellow
Risk Matrix		Minimal (1)	Minor (2)	Medium (3)	Major (4)	Very High (5)
			Consequence			

FIGURE 7.1
Risk Management 5×5 Matrix.

Board Actions

One of the key decisions made at the risk meeting is the board action for each risk discussed. Once a risk is accepted into the risk management system, it is actively managed to prevent its occurrence or minimize the impact should it become a problem. However, there is a point in the process where the returns are diminished. Whether a risk is accepted, closed, elevated, or rejected, it must be documented so that everyone on the team understands the rationale.

Accept: This option indicates that the project has elected to take the risk without further action. Risk acceptance is dependent on the project, risk environment, and mission risk classification as established by the sponsor. Only the project manager can accept risks, although the risk board chair and risk manager are consulted for technical risks. For risks that have a moderate or high severity, it is recommended that acceptance also requires concurrence outside the project from a chief engineer or mission assurance supervisor. The rationale for the risk must demonstrate that all reasonable mitigations options (within cost, schedule, and technical constraints) have been instituted. Accepted risks represent the residual risk for the project and should continue to be tracked within the database, with an increase in risk severity triggering a re-review of the risk.

Close: A risk is closed when one of the following occurs: (1) when the risk is reduced to a negligible likelihood or consequence; (2) when the risk materializes as an issue/problem that is tracked, managed, and resolved outside of the risk management process and in other technical or programmatic processes; or (3) when the risk can no longer occur. The project manager approves the closure of a risk with concurrence from the lead systems engineer, and closed risks remain in the risk database with a rationale for closure.

Elevate: Risks may be raised from element-level risk boards to the risk project board for several reasons. Typically, the following types of risks should be raised: (1) risks with a certain predefined severity level or greater; (2) risks that require higher-level intervention or mitigation; (3) risks that affect project safety, technical performance, external interfaces, resources, or schedule; and (4) risks that impact another element.

Reject: Potential risks that are brought to the risk board may be dismissed if it is determined that the consequence and likelihood of the concern are not sufficiently high to warrant being a risk or that the issue brought forward does not constitute a risk but rather an aspect of typical technical or programmatic activity.

Risk Actions

Once the risk has been assessed with regard to likelihood and consequence, the project manager or risk board chair assigns the risk to a project team member. The person assigned the risk is then responsible for all aspects of managing the risk, which includes further characterization or research into the risk, refinement of mitigation plans, tracking and updating the risk, and reporting a status of the risk to risk board. The status of risks is typically tracked using one of three options:

1. *Research*: This option indicates that analysis is required to improve the knowledge of the risk exposure or that a risk mitigation plan is under development. In either case, an action due date (or trigger date) must be established for completing research or developing a mitigation plan.
2. *Watch*: In this option, the assignee continues to monitor the risk, looking for changes in either the likelihood or potential impact of the risk. A contingency plan may be developed pending future risk evaluations. Significant variations in the risk severity (up or down) should be immediately reported to the risk board chair and the risk manager for reevaluation.
3. *Mitigate*: This status is used when a contingency plan is initiated. If and when the mitigation plan has been implemented, and the risk meets the closure criteria defined earlier, then the risk item can be closed. If the risk remains at a reduced level, the project can choose to continue monitoring the risk or accept the residual risk.

Formally Defined Processes

CRM

Continuous risk management (CRM) is a risk management process introduced to NASA in the mid-1990s. The CRM process focuses on the implementation of selected alternatives to ensure that project requirements are met and entails the continuous management of risks throughout all phases of the project. The CRM process has five distinct functions: identify, analyze, plan, track, and control, as shown in Figure 7.2 [1].



FIGURE 7.2
The continuous risk management (CRM) process. (Data from NASA-SP-2010-576, *NASA Risk-Informed Decision Making Handbook*, April 2010.)

RIDM

Risk-informed decision making (RIDM) is another risk management process introduced to NASA in the 2010 timeframe. RIDM was introduced as a complementary process to CRM that is primarily concerned with the quantitative analysis of decisions. RIDM addresses the risk-informed selection of decision alternatives to assure effective approaches to achieving objectives and can be thought of as the front-end of the risk management process (i.e., setting the stage for CRM). There are three parts to the RIDM process, as shown in Figure 7.3: identification of alternatives, risk analysis of alternatives, and risk-informed alternative selection.

Part 2 of the RIDM process is where performance measures of each alternative are quantified, taking into account the uncertainties related to the selection of the alternative and the accomplishment of the objectives. Given the presence of uncertainty, risk analysts must model each possible outcome, accounting for its probability of occurrence, producing a distribution of outcomes for each alternative (typically characterized by probability density functions (pdfs) over the performance measures). Some of the tools and methodologies used by the risk analyst include parametric cost estimating, engineering buildup method, detailed simulation estimating, and detailed logic modeling estimation (i.e., probabilistic risk assessment or failure modes effects and analysis).

The CRM process uses the results of RIDM to address the implementation of the selected alternative to assure that requirements are met. Figure 7.4 shows the integration between the RIDM and CRM processes into a single coherent framework for risk management [2].

ISO 17666

ISO 17666, *Space Systems—Risk Management*, is the international standard for defining the principles and requirements for integrating risk management into space projects. ISO 17666 defines risk management as a systematic and iterative process for optimizing resources that are incorporated through defined roles and responsibilities into the

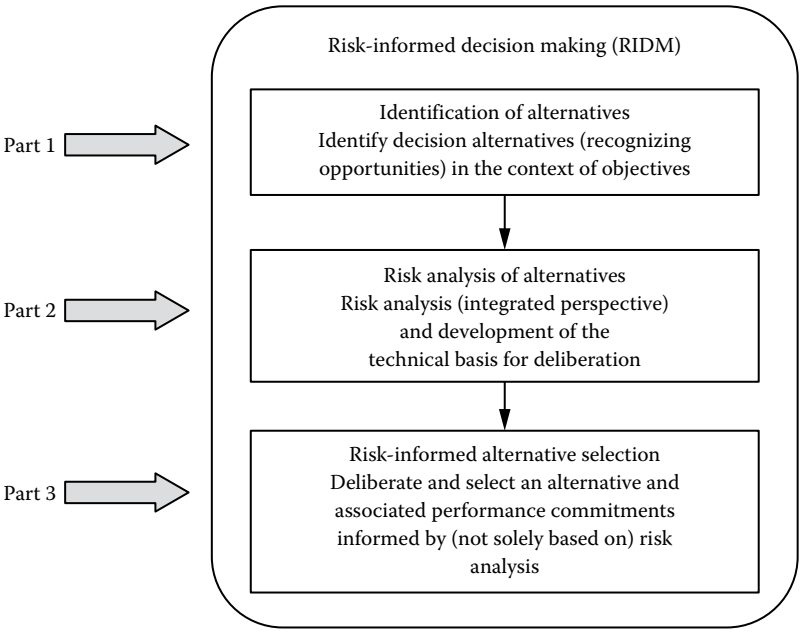


FIGURE 7.3
The risk-informed decision making (RIDM) process. (Data from NASA-SP-2010-576, *NASA Risk-Informed Decision Making Handbook*, April 2010.)



FIGURE 7.4
Risk management as the interaction of RIDM and CRM. (Data from NASA-SP-2010-576, *NASA Risk-Informed Decision Making Handbook*, April 2010.)

day-to-day activities of the project, throughout the project life cycle. The implementation of this process is scalable to project-specific conditions.

ISO 17666 subdivides the risk management process into four main steps: (1) define risk management implementation requirements, (2) identify and assess the risk, (3) decide and act, and (4) monitor, communicate, and accept risks. These steps are then further broken down into tasks. Figure 7.5 shows these steps as a cycle throughout the project.

RM Plan

For more formal risk management systems, a risk management plan is recommended to document the role risk management plays in the project and to ensure that risks associated

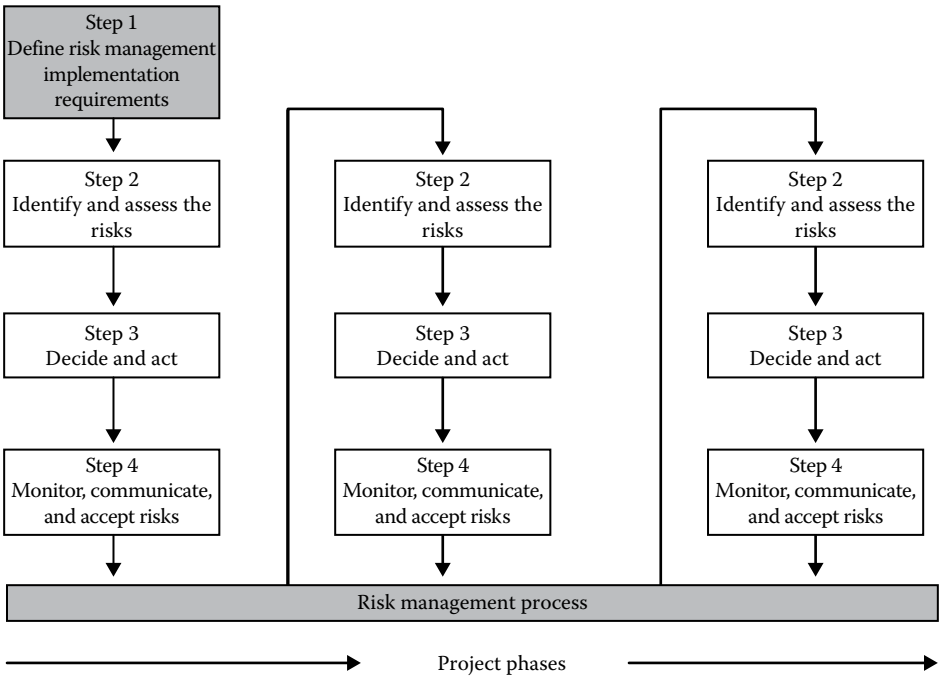


FIGURE 7.5
Steps and cycles in the ISO 17666 risk management process. (Data from ISO 17666:2003, *Space Systems—Risk Management*.) https://iso.org/obp/ui/#iso:std:iso:17666:ed-1:v1:en. ISO 2003.

with the project are identified, analyzed, monitored, and appropriately mitigated. A typical risk management plan should include the following:

1. Introduction
   a. Purpose of document
   b. Related documents
2. Risk types
   a. Technical
   b. Schedule
   c. Cost
   d. Safety
   e. Programmatic
3. Risk management process
   a. Roles and responsibilities
   b. Description of the closed-loop process for identifying, handling, and tracking risks
   c. Methods and tools used
4. Risk documentation
   a. Risk database
   b. Risk metrics

What Can Go Wrong?

The project manager must ensure that the processes put in place and the analyses chosen are sufficient to properly guide the project's decisions without turning the risk management into such an extensive analytical effort that it becomes a project risk itself. Similarly, the risk board must meet with sufficient frequency to enable an active risk discussion forum without taking so much time from team members that their development efforts are constrained. A successful risk management program will carefully walk the line between sufficient risk analysis and oversight and costly overanalysis and programmatic burden.

References

1. SEI, A.J. Dorofee et al., *Continuous Risk Management Guidebook*, Carnegie Mellon, Pittsburgh, PA, 1996.
2. NASA/SP-2010-576, *NASA Risk-Informed Decision Making Handbook*, April 2010; NASA/SP-2011-3422, *NASA Risk Management Handbook*, Washington, DC, November 2011.

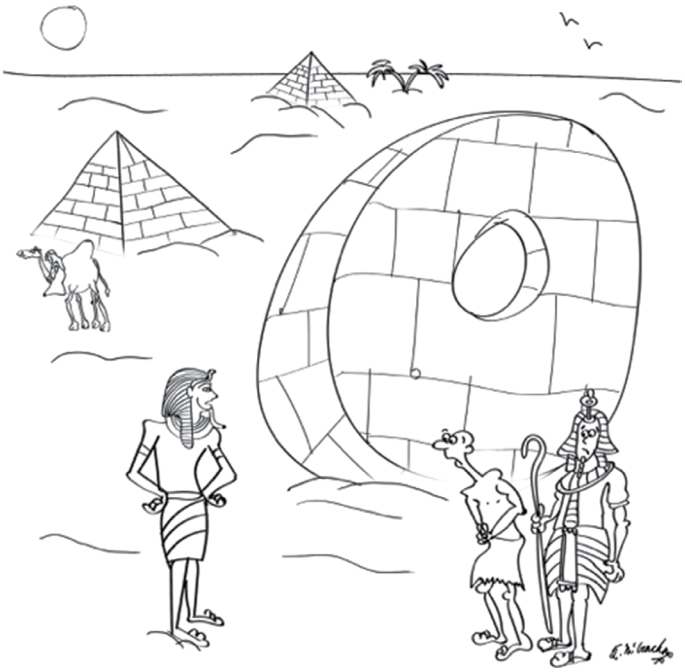
8

Configuration Management

Jennifer Fischer

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"YOU DIDN'T GET THE CHANGE NOTICE, DID YOU?"

A comprehensive process for establishing and maintaining the consistency of any product's performance, functional, and physical attributes with its requirements, design, and operational information [1].

What is Configuration Management?

Configuration Management (CM) is a foundational activity that must be effectively implemented throughout the entire life cycle of programs and projects in the aerospace industry. The importance of CM has been established and promoted through the development of many industry and government standards, which all conclude that the process of planning, identification, structuring, managing change, and verification is of critical importance and spans all disciplines within a project. By understanding the basics of CM and utilizing the tools available, program managers can effectively manage and productively achieve a sound basis for a project's success.

The concept of CM began during missile development in the 1950s. Difficulties regarding the production and manufacture of missiles within the United States Department of Defense stemmed from the lack of repeatable process or the ability to replicate products in an efficient manner. Change control was introduced to understand and coordinate changes made to the engineering design. The addition of assessing cost and schedule implications and how the changes affected other designs within a system led to the implementation of CM [2]. This resulted in the development of Army, Navy, Air Force (ANA) Bulletin No. 390 and 390A in 1953, which defined the Engineering Change Proposal or ECP. After many iterations and additions, they evolved to become MIL-STD-480, which has been superseded by several iterations, including MIL-STD-973 [3]. On September 30, 2000, MIL-STD-973 was canceled, after which the Department of Defense adopted ANSI/EIA-649 National Consensus Standard for CM to implement the best practices and processes employed by industry. CM is now practiced worldwide, and its concepts have been adopted by many specific standards and disciplines associated with process and product quality, including, but not limited to:

- Aerospace Standard AS9100
- International Organization for Standardization ISO 9001
- Capability Maturity Model Integration (CMMI)
- European Space Agency (ECSS-M-ST-40C)
- Federal Aviation Administration (FAA Order 1800.66)
- ISO/IEC 15504 Information Technology

CM Process

Any valuable process needs a clear, consistent, and implementable set of elements or activities that safeguard against errors or inconsistencies. Figure 8.1 shows the five elements of the process.

The five main elements of the CM process are:

1. Configuration Management Planning
2. Configuration Identification
3. Configuration Control/Change Management
4. Configuration Verification
5. Configuration/Status Accounting

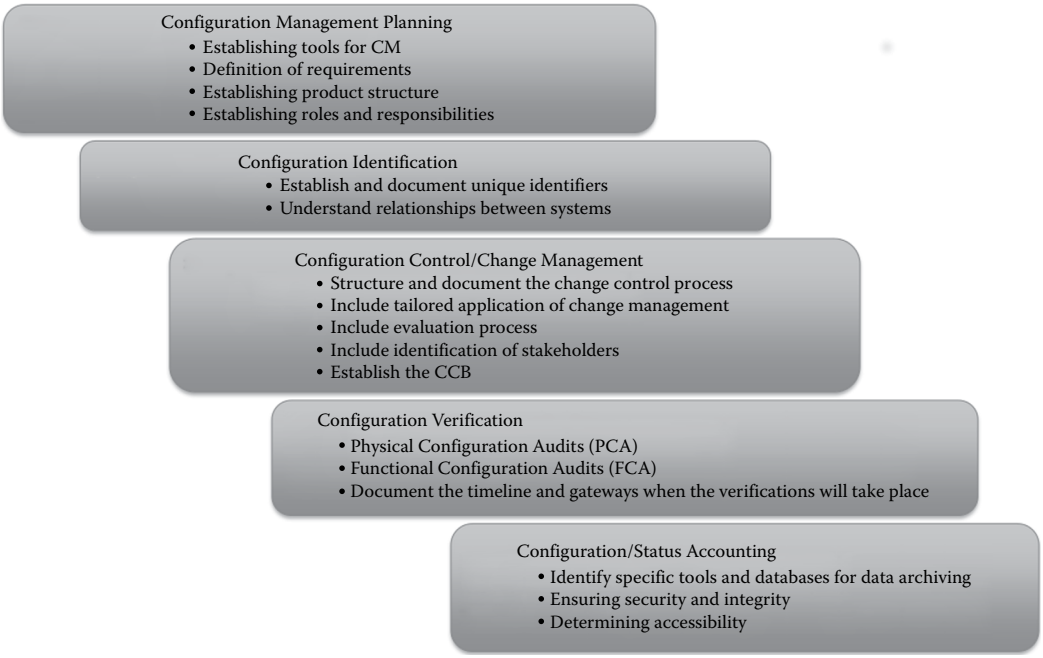


FIGURE 8.1
Configuration Management process.

Configuration Planning

Configuration Planning is a coordinated set of activities to direct and control configuration of a end item to include planning of the processes, tools, and products that need to be configured for an individual project. Often the general processes and procedures for CM may be defined at an institutional level, but may require tailoring for a particular customer or program. Many versions of CM-based tools are available. However, most organizations have a standard software tool that is used to manage the CM effort. Available tools range from extensive, complex tools to simpler tools that do not have the same control capabilities. The right tool for a project will depend on the size, scope, complexity, and risk tolerance of the project. Whatever tool is used, it usually must be organized and sometimes programmed with information-specific details, such as program identification accurate data or permissions depending on the documentation being placed under configuration control. This is the phase of CM where the documentation requirements, both external and internal as well as the physical configuration of the system, are defined and recorded in the product structure and the list of configuration items. The configured items (CI) are the specific article(s) that satisfy the final delivery or end item result. This list should also include what specific components will be placed under configuration control (hardware, software, ground support equipment [GSE], plans, or documents).

CM processes must be scalable. Understanding the end goal of a project and what rigor must be applied to successfully achieve the intended objective helps define the level of CM needed and thereby specific requirements that should be implemented to provide control. Once the requirements are identified and understood, not only what will be

managed within the configuration management system, but also the scale that will be appropriately applied—it should be documented. This can take the form of a project specific CM plan, memos outlining key roles and responsibilities, templates, tools, etc. By documenting the specific process that will be implemented on the project, a clear communication path is defined that will help to establish an effective process and reduce errors and miscommunication.

Configuration Identification

Configuration Identification is an activity wherein items placed under configuration control are given unique identifiers based on physical, functional, or requirement characteristics, their relationships to each other as well as the creation of the project baseline. Configuration Identification ensures that the individual designs and documents are managed independently and without misinterpretation. Unique identifiers for each configured item ensures that each requirement, procedure, design, etc., can be individually created, released, managed, and verified to safeguard against miscommunication leading to costly quality and schedule escapes. Configuration Identification also works in conjunction with the product structure. Product structure is the accounting of the entire design, whether physical or functional, that will make up the final product, made up of all individual entities and their interrelationships (Figure 8.2).

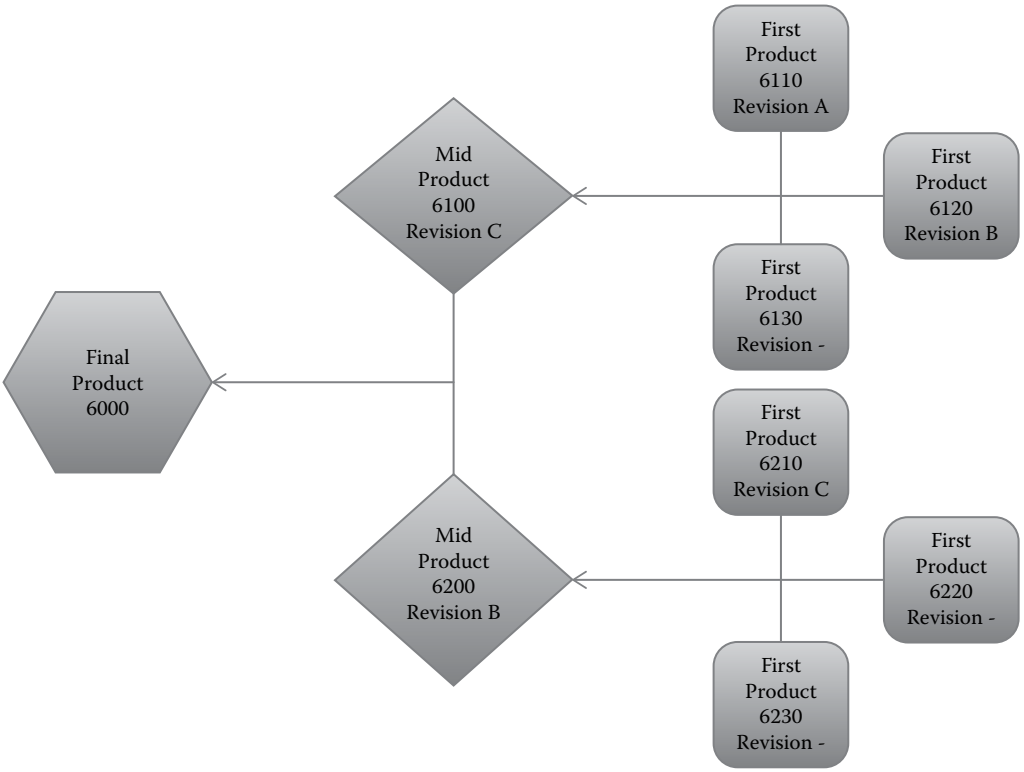


FIGURE 8.2
Product structure and relationship of configured items.

Having clearly identified configuration items is a cornerstone of any CM system. Lack of identification for CI leaves a project open to concerns about which products should and which products did become part of the end item. As soon as possible, the project's CI should be identified as part of establishing the product baseline. A configuration baseline is a fixed reference configuration established by defining and recording the approved configuration documentation for a System or CI at a milestone event or at a specified time [4].

Configuration Control/Change Management

Change Control/Change Management is the process of controlling, documenting, and storing the change to controlled items. This includes proposing the change, evaluating it, approving or rejecting, and documenting the final disposition of the change.

Change Management is basically controlling changes to the product baseline. During the life cycle of a project, alteration of the product baseline is often required. Lack of a structured change management process can affect the physical or functional attributes of a design and the overall efficiency of project operations. Once the CI have been identified, and a baseline has been created, the next step is to ensure that any changes are managed and controlled. This is as important as the initial creation, in that if a configured item has uncontrolled changes, it is no longer configured and its defining information may be inaccurate. For example, consider a document that contains requirements for fabrication that has been reviewed and released by the necessary stakeholders. These stakeholders have agreed on the technical content of the document. That document has been released to the fabrication floor with this understanding. However, for instance, if an e-mail is sent to the fabricator changing a technical aspect of the drawing, this could hypothetically affect the next higher assembly, as an example. Without this change undergoing the proper evaluation, communication, and documentation via an established revision process, the configuration of the actual product is unclear during verification and could have technical ramifications that the next higher assembly is unaware. Additionally, changes could have cost and schedule implications that are not immediately apparent, including some that may potentially affect customer requirements. These issues would be resolved as part of an effective change control process (Figure 8.3).

A common misconception in project management is that the change management process is complicated, time consuming, and expensive. However, proper planning can help tailor the process, so it meets the needs of the project in the most efficient manner possible. The main steps in any change to CI consist of recognizing the need for a change, communicating the need for the change to the necessary individuals, document the change, evaluating the change, approving the change, documenting the approval, implementing the change, and verifying the change was accurately incorporated [5]. A Change Control Board (CCB) should be established to ensure that all necessary participants participate in the change management process. Depending on the project, the change management process may be formal or informal; however the same general process steps are applied.

The change management system should be tailored to fit the need of a particular project. Not all changes are equal and depending on the requirement affected, some changes may have more severe implications and higher visibility within the project. Defining different levels or classes of change, and the attending Change Management process requirements assists in ensuring that the proper audience is involved in the evaluation process.

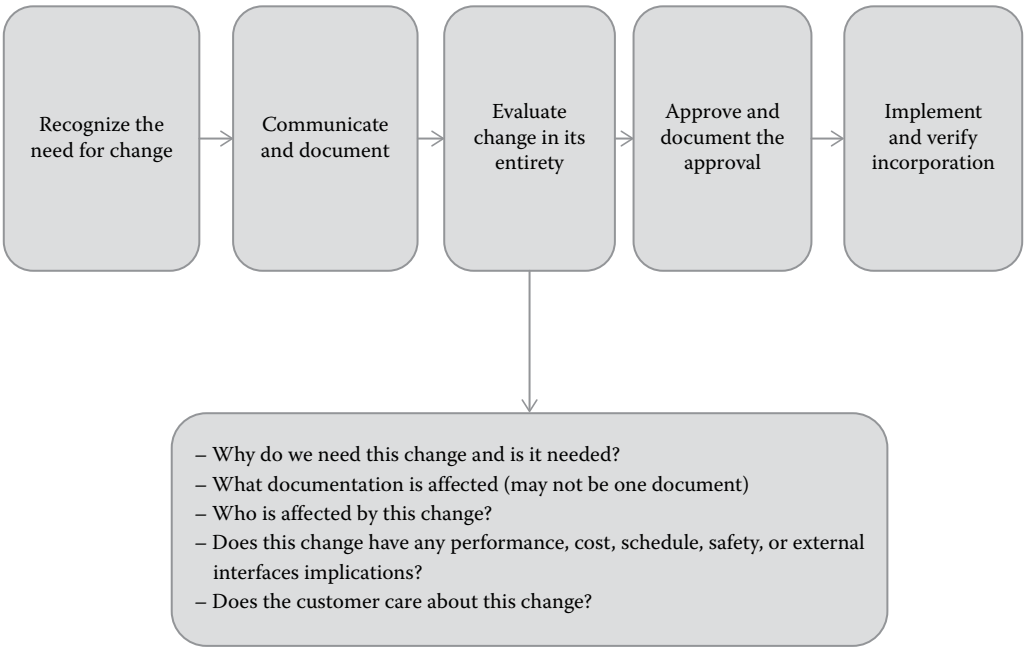


FIGURE 8.3
Steps in a Change Management.

Configuration Verification

Configuration Verification consists of a series of checks and balances throughout the life cycle of the product to ensure functional and physical accuracy and overall confirmation that the end item meets the requirements of the project and the customer. Two different types of configuration audits exist—Physical Configuration Audit (PCA) and Functional Configuration Audit (FCA). A PCA is a formal review or audit verifying that the as-built configuration of a product matches the as-documented design. An FCA is a formal review or audit and verifies that the final tested product conforms to the documented requirements, including performance requirements [6].

Verifications should be done incrementally and periodically throughout the manufacturing process to verify compliance before integration into the next higher assembly, as defined in the product structure. Independence during this process allows a unique and impartial view of the data presented in the as-built, as-run, or final configuration. Much like the other steps in the CM process, documentation becomes very important, not only to prove the intended physical and functional requirements have been met, but also to provide objective evidence that the overall product is complete.

Configuration/Status Accounting

Configuration or Status Accounting is the management of all the data that are produced during the CM process. Status accounting can provide an understanding of where each design is in the life cycle of the product. Maintaining specific tools or databases as defined by the project is vital to this process to ensure that data are not only maintained, but are managed and archived for the duration of the project by the contractual requirements.

This function can identify the status of each item in the configuration baseline during the project's life cycle. Some pitfalls that should be considered when establishing the status/accounting system include

- Ensuring security and integrity of the system that maintains and archives the data
- Determining accessibility (which may be restricted depending on the contract) to project libraries or design information

Making the CM Process Work Efficiently and Effectively

Several significant inputs to the configuration management activity will ensure a clear, well-defined, productive process. Particularly important are well-defined data points at the beginning of the process, such as

- Defining the levels of configuration and the pertinent stakeholders at each level
- Identifying and defining authorities for approvals
- Documenting the process in a Configuration Management Plan (CMP) or within other appropriate project documentation
- Identifying, developing, and maintaining the project-defined databases that will be used in the management of the CM process

Challenges for CM

The CM process can be a useful and productive addition to the project arsenal of tools to achieve success. However, challenges do exist and can be overcome if considered early in the process.

1. *Process consistency*: At the beginning of each project, there may be a tendency to reinvent the wheel, which leads to higher costs and perceived a lack of value added. Using lessons learned from past programs and establishing a well-defined process early on in the project can ensure a consistent approach that adds value to each phase of the project. Organizations should also establish repeatable processes that are scalable and tailorable to meet the needs of all projects in their portfolio. Tailoring should not result in individual projects establishing radically different approaches to CM. Standardization (where it makes sense) can lead to process efficiencies.
2. *Adequate staffing*: Projects sometimes understaff the CM function, not realizing how much behind-the-scenes activities are performed to ensure that the article being distributed is accurate. A project never wants to be in the position of wondering what was done/required/designed/built when the time comes to answer important questions or, just as importantly, repeat the process.

3. *CM throughout all project life cycle phases*: CM contributes to a project's success throughout the project's life cycle. While the function is critical at the beginning of a project, it continues to maintain its importance until the very end. Despite the end-of-project schedule crunches that affect many aerospace projects, CM rigor must be maintained. Effective CM requires the support of the entire project team, so ensuring that all contributors to the product maintain not only the product integrity, but the configuration throughout the build, results in a smoother, more efficient transition at the end.

In summary, CM serves as a vital communication tool for not only project/program managers, but also for the entire project team by

- Establishing a process for base-lining project information
- Ensuring all stakeholders are aware of the requirements for design, development, integration, test, operations, and disposal
- Managing the changes to the controlled information
- Verifying that controlled information is accurate and meets the intended end goals of the program

CM acts as a bridge among functional groups supporting a project, including management and engineering, engineering to manufacturing/fabrication, or quality/safety and mission assurance and manufacturing. CM ensures that the product can be integrated at increasing levels of assembly. It is the bookmark to ensure that everyone is on the same page. When effectively implemented, CM should be a communication tool that can help a project manager manage the timeliness, quality, and overall cost of the end product.

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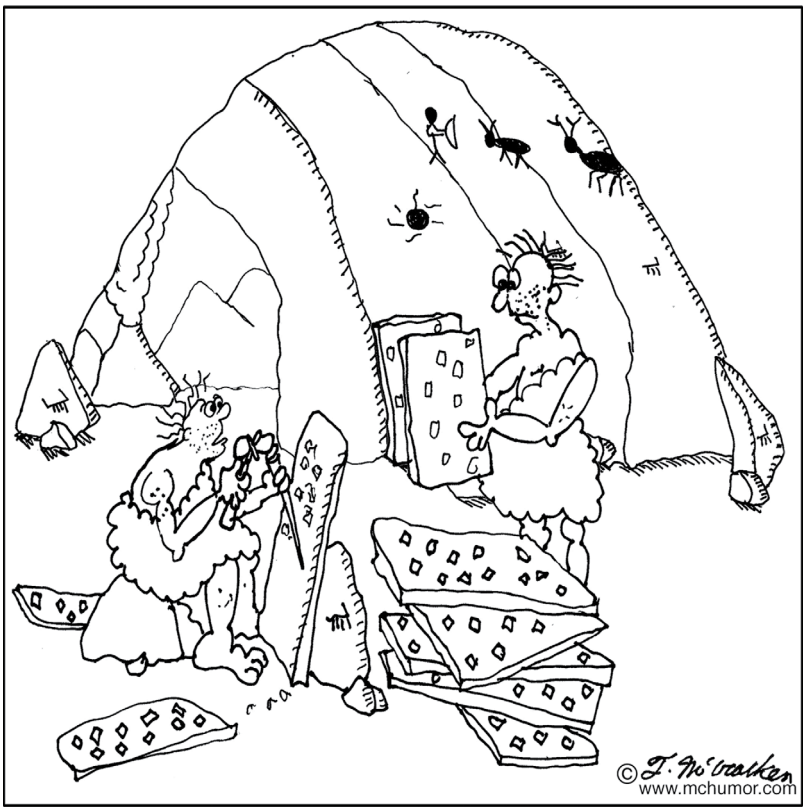
9

Government Sponsor Imposed Requirements

Michael Ryschkewitsch

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"WHAT YOU MEAN THE SPECS
ARE BEING CHANGED AGAIN?!?"

Overview

As modern projects increased in complexity and the consequences of any failure increased, the need to communicate and track requirements across large organizations and over long development cycles became more acute. The processes for managing and engineering the development of large complicated systems evolved together. In aerospace, this trend accelerated during the middle years of the twentieth century, especially with the development of intercontinental ballistic missiles and large space projects such as the Apollo Program. It is no accident that Simon Ramo is regarded by many as both the father of the intercontinental ballistic missile and of modern systems engineering. Similar approaches evolved in the civilian realm with the Apollo Program as the quintessential example [1]. In addition to the needs of governing the technical development and the resources needed for it, government projects are conceived and executed in a complex environment in which the agencies and upper levels of the Administrative Branch and the Congress reach an agreement on the budget priorities, goals, and constraints. Those are normally codified in Authorization and Appropriations bills. In addition, both branches have developed regulations, reporting, and decision making processes to support their needs. All of these are captured and imposed on programs and projects as requirements.

Most U.S. Government organizations that sponsor aerospace programs and projects impose procedural requirements that govern how those projects are executed and how decisions are made to authorize beginning, continuing, and ending those projects. The word "project" is used generically here to describe an activity with a beginning, an end, and a deliverable product. There are a number of definitions of programs and projects and their relationships that will not be covered here. The most widely used and taught are those of NASA used for spaceflight projects and the Department of Defense (DoD) used for a wide range of projects including spaceflight projects, sensor, and weapon systems. Some other organizations have adopted or adapted these or developed versions of their own. This chapter will briefly describe the NASA life cycles as described in NASA Space Flight Program and Project Management Requirements (NASA NPR7120.5E) and briefly compare them to the DoD 5000 documents, which include the Life Cycle Processes and then focus on the NASA process to allow more in-depth discussion. Safety and mission assurance requirements and technical and systems engineering requirements are covered in Chapters 6 and 10, respectively. For Government entities such as the DoD Laboratory or NASA Center, the requirements of these documents are normally imposed directly. For others (a company, Federally Funded Research and Development Centers (FFRDCs), University Affiliated Research Centers (UARCs), University, etc., they are imposed to the extent that they are invoked in the contract, grant, or other agreement used to define the terms of the agreement between that entity and the Government.

The requirements contained in these documents are of three types:

1. Requirements originating with the governing agency describing types and sequencing of activities to be performed and products to be generated to support the program/project development
2. Requirements originating with the governing agency describing decision making external to the program/project and the information required to support that decision making
3. Requirements originating external to the Agency and imposed on a Project to comply with law, regulation, or governing policy (e.g., earned value management)

The first two categories are derived from lessons learned in executing previous projects and are imposed to ensure that due diligence is executed in applying taxpayer funds to achieve the goals of the project and that parties charged with overseeing or auditing those developments have proper visibility and control. Both NASA and the DoD use a phased life cycle with decision points or gates between the phases to verify that the Project's work is correct and sufficient to prepare for the next phase. In each phase the technical requirements, designs, analyses, etc., are refined and developed in greater detail to support the eventual production and delivery of the desired product. Similarly, the project's plans for all of the activities are successively developed and refined to ensure delivery of a known quality of product to meet objectives within cost and schedule constraints. Preparatory to a decision gate, all of these are reviewed to ascertain that (1) the desired progress has been made and (2) the plans support the activities to be executed in the next phase and over the full remainder of the life cycle. The decision maker will determine from the data presented if the Project is sufficiently likely to meet its objectives within the cost and schedule constraints to proceed to the next phase and give authorization to proceed with or without corrective actions or decide to terminate the Project. Additional timing constraints may be imposed to synchronize with the sponsoring organization's budgeting process.

The DoD life cycle is described in DoD Instruction 5000.02 and shown schematically at a very high level in Figure 9.1 of the DoD 5000.02. The similar NASA pictorial follows it. The overall logical flow of the DoD and NASA processes are similar in that they begin with defining a need, explore ways of meeting that need, develop the technology required to implement the desired solution, develop the product, put the product into use, and eventually dispose of the product after it is no longer needed or can no longer fulfill its intended purpose.

The principal difference is that the NASA process accommodates developing both operational and research systems but is most commonly used for the acquisition of research

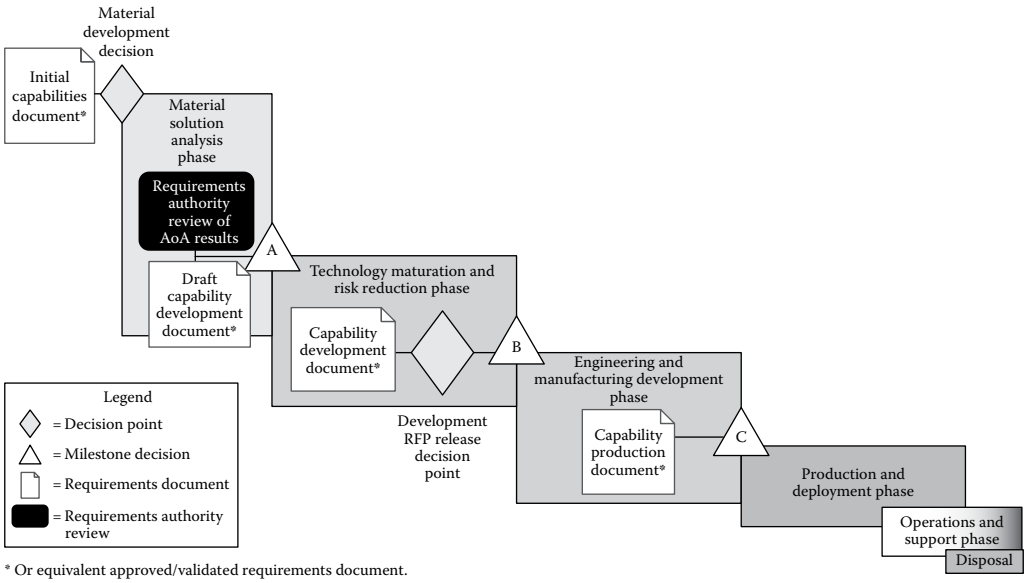
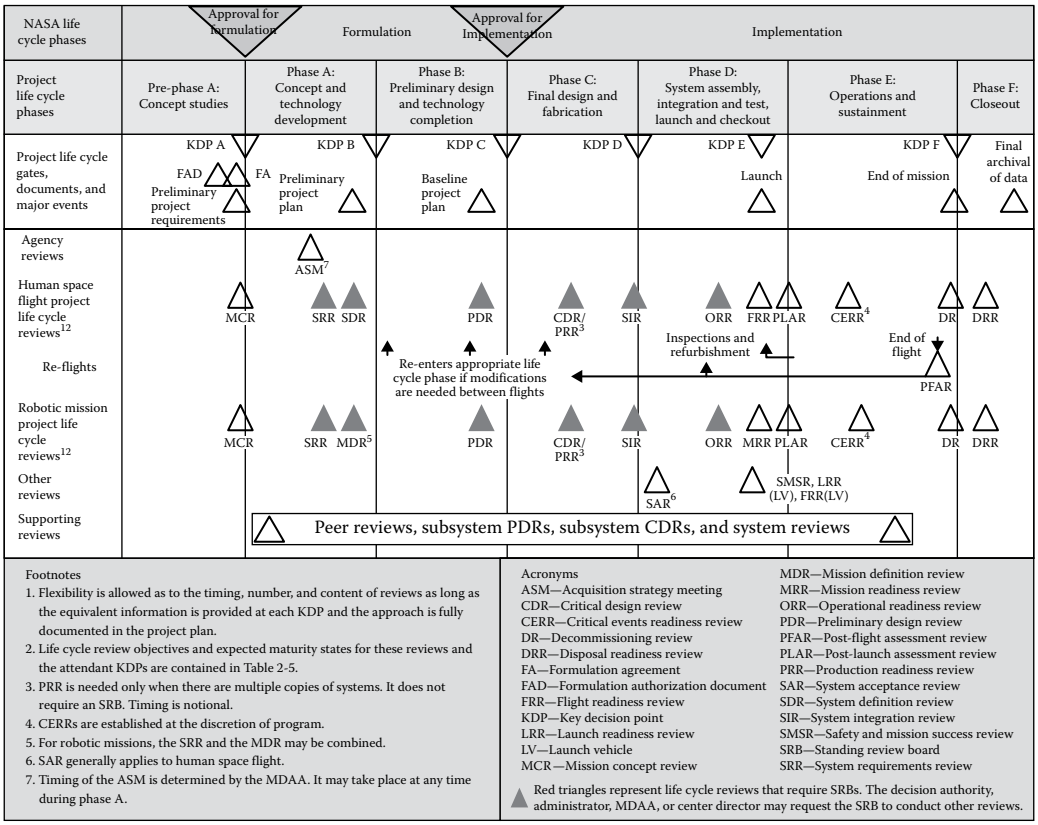


FIGURE 9.1
Illustration of the interaction between the capability requirements process and the acquisition process (DoD).

systems ("one of a kind" or small number production runs). The DoD process is more commonly focused on operational systems in which the objective is delivering a production run of small to large numbers and most often sustaining the operational system(s) over long periods of time. The remainder of this chapter will focus on the NASA life cycle (Figure 9.1).

The NASA-phased life cycle is an overlay, evolution, and adaption of the modern systems engineering methodology that evolved during the 1950s and the 1960s. The fundamental learning of that period was that space systems and space launch systems were complicated, costly, required large development teams, and that the consequences of a failure were usually catastrophic. Taken together this meant that new processes were needed to design, test, and deploy these systems with an adequate prospect of timely success (Figure 9.2).

The phased breakdown methodology was developed in which the team successively analyzed and evaluated alternative approaches, first at the macro level, and then developed the preferred alternatives to successively great levels of detail. Complexity and communication were dealt with using product breakdown structures, interface controls, hierarchical requirements flow downs, etc. Similarly the project manager had to develop more detailed plans for activities and schedules to coordinate them for the full duration of the development as well as to support budget and schedule estimation and tracking.



Footnotes
1. Flexibility is allowed as to the timing, number, and content of reviews as long as the equivalent information is provided at each KDP and the approach is fully documented in the project plan.
2. Life cycle review objectives and expected maturity states for these reviews and the attendant KDPs are contained in Table 2-5.
3. PRR is needed only when there are multiple copies of systems. It does not require an SRB. Timing is notional.
4. CERRs are established at the discretion of program.
5. For robotic missions, the SRR and the MDR may be combined.
6. SAR generally applies to human space flight.
7. Timing of the ASM is determined by the MDAA. It may take place at any time during phase A.

Acronyms
ASM—Acquisition strategy meeting
CDR—Critical design review
CERR—Critical events readiness review
DR—Decommissioning review
DRR—Disposal readiness review
FA—Formulation agreement
FAD—Formulation authorization document
FRR—Flight readiness review
KDP—Key decision point
LRR—Launch readiness review
LV—Launch vehicle
MCR—Mission concept review
MDR—Mission definition review
MRR—Mission readiness review
ORR—Operational readiness review
PDR—Preliminary design review
PFAR—Post-flight assessment review
PLAR—Post-launch assessment review
PRR—Production readiness review
SAR—System acceptance review
SDR—System definition review
SIR—System integration review
SMSR—Safety and mission success review
SRB—Standing review board
SRR—System requirements review

Red triangles represent life cycle reviews that require SRBs. The decision authority, administrator, MDAA, or center director may request the SRB to conduct other reviews.

FIGURE 9.2
Illustration of the interaction between the capability requirements process and the acquisition process (Data from NASA).

Since the technical and programmatic processes mirror and support each other, the planning process took on the same phased breakdown methodology. Those methodologies are framed and summarized as the "life cycle model."

Description of the Phases and Decision Gates

Within the life cycle model, there are three "NASA Life Cycles Phases" further divided into project phases. The life cycle phases are "Pre-Formulation," "Formulation," and "Implementation." The Life Cycle Phases are separated by the Key Decision Points (KDP) A, B, and C. For a Project, KDP-A marks its authorization as a NASA project to develop a product. KDP-C marks the transition of the Project from defining the product to be created and the plans to do so and the actual implementation of those plans to develop the product. For a Project, the Phases are subdivided into Phases labeled A–F as summarized here:

1. Pre-Phase A—Activities performed to determine that there is at least one concept of a solution which is likely to meet the need within constraints.
2. Phase A—Determine the best way to meet the need within constraints.
3. Phase B—Perform the system trades and preliminary design to define the system that will be implemented to meet the need.
4. Phase C—Perform detailed design and implementation of the system intended to be built, assembled, and tested.
5. Phase D—Assemble, test, and prepare for deployment of the system.
6. Phase E—Deploy, commission, and use the system to meet the need.
7. Phase F—Dispose of any remaining assets and close out the related activities.

A Decision Memorandum resulting from a Key Decision Point Meeting authorizes transitioning from one phase into the next. The Decision Authority at that meeting is informed of the work accomplished and the plans (including cost and schedule) for accomplishing the remainder of the work and determines whether the project can proceed and gives guidance as necessary. Normally, the highest level KDP meeting is preceded by a series of technical and programmatic reviews to assess the quality and quantity of work products and plans. The results of these reviews are summarized for the Decision Authority including the decisions and recommendations from any subsidiary authorities such as a Center or Mission Directorate. This process creates a "season" of activities which should be kept as short as possible to minimize disruption of the project and the risk of changes directed by the Decision Authority.

Tailoring

> Plans are worthless, but planning is everything
>
> **—Dwight D. Eisenhower [2]**

Developing a set of program or project plans that are compliant with the applicable governing policies and documents requires thoughtful work. NASA provides a valuable set of reference materials that provide the context and guidance useful in developing plans. Special Publication NASA/SP-2014-3705, NASA Space Flight Program and Project

Management Handbook and NASA/SP-2007-6105, NASA Systems Engineering Handbook are especially useful and can be accessed along with a number of other useful reference documents from the NASA NODIS Library [3]. Another relevant set is provided in the NASA NODIS 8700 series available from the same link. In general, the plans will describe how the applicable requirements will be met and the normal signature process authorizes tailoring. If an applicable requirement cannot be met, the policies lay out waiver and deviation processes for approval. In general, it is important that the needed approvals for deviations and waivers be sought as soon as it is known that one will be needed so that the waiver authority has the maximum flexibility in their decision process. In all cases, the most fundamental tenet is to lay out the plan needed for the project in coordination with the stakeholders, having them logically derived and at each point being able to elucidate the risk/reward proposition.

In general, programs and projects with larger budgets and of strategic importance to operations and strategic plans or of high public visibility will require more detailed and more formally documented plans. Such activities commonly employ larger and more widely dispersed teams and the plans are needed for coordinating their activities and managing risk in a complex project environment. Smaller projects and smaller teams will generally require less detail and formality.

The NASA Associate Administrator determines the categorization of a program or project based on its budget and risk categorization as show in Table 2.1. of NASA 7120.5E. NASA defines acceptable risk as the risk that is understood and agreed to by the program/project Governing Program Management Council (GPMC), Mission Directorate, and other customer(s) such that no further specific mitigating action is required beyond those already executed and/or planned. All parties are better able to understand the acceptable risk associated with a program or project when authorization documents and Level 1 requirements include information regarding the relative risk level are made clear very early in the life cycle giving the implementing organization guidance for developing plans. This will often be cited as the category and risk class, for example, "Cat 2, Class C." The intention is to set expectations for the development of plans [4] (Table 9.1). The NASA Risk categorization and characteristics are defined in Appendices B and C of NASA NPR 8705.4 [5]. The table from Appendix B is shown in Table 9.2.

TABLE 9.1

Project Categorization Guidelines

Characterization	Class A	Class B	Class C	Class D
Priority (criticality to agency strategic plan)	High priority	High priority	Medium priority	Low priority
National significance	Very high	High	Medium	Low to medium
Complexity	Very high to high	High to medium	Medium to low	Medium to low
Mission lifetime (primary baseline mission)	Long, >5 years	Medium, 2–5 years	Short, <2 years	Short, <2 years
Cost	High	High to medium	Medium to low	Low
Launch constraints	Critical	Medium	Few	Few to none
In flight maintenance	N/A	Not feasible or difficult	Maybe feasible	Maybe feasible and planned
Alternative research opportunities or re-flight opportunities	No alternative or re-flight opportunities	Few or no alternative or re-flight opportunities	Some or few alternative or re-flight opportunities	Significant alternative or re-flight opportunities

TABLE 9.2

NASA Project Life Cycle

Priority Level	LCC < $250M	$250M < LCC < $1B	LCC > $1B, Significant Radioactive Material, or Human Space Flight
High	Category 2	Category 2	Category 1
Medium	Category 3	Category 2	Category 1
Low	Category 3	Category 2	Category 1

Source: NASA, NASA Space Flight Program and Program and Project Management Requirements NPR7120.5E (NM 7120-81).

Review Boards

NASA uses review boards with members having relevant expertise to assess the status, progress, and plans of the activity under review. For most programs and projects, NASA will convene a Standing Review Board (SRB) for the life cycle of the project to ensure consistency of review. The SRB is chartered via Terms of Reference that gives the SRB salient guidance in conducting their reviews. In all cases, the SRB is expected to both help the project improve their plans and to inform all parties in the decision chain of the status versus expectations for that point in the life cycle, risks, mitigation plans, and potential consequences and offer suggestions for improvements. The SRB also independently assesses the cost estimates and the cost and schedule risks. The SRB chair provides the assessment(s) and evaluation(s) to the program/project under review, and all parties in the chain of authority. Review boards do NOT generate requirements or issue approvals.

Types of Announcements and Agreement

NASA uses a number of methods for entering into agreements to do work. Each will have its own requirements. The requirements in the resulting agreement generally supersede otherwise applicable policy requirements, but often will invoke them or give guidance on how they should be interpreted or tailored. A very brief definition is given for the most common, in approximately increasing order of the number and stringency of requirements imposed.

Requests for Information (RFI)—A request for interested parties to provide information about a specific topic. Often this is used early in the planning process to determine the capabilities and interests of potential development organizations and available technologies and/or capabilities. An RFI is not a commitment by the Government nor is the response a commitment by the responder but it is expected that all parties will act in good faith.

Grants—An agreement without a specified deliverable, generally used for conducting research. The recipient agrees to do work as was proposed to receive the grant and for the purposes described in the grant. Deliverables are generally a report describing the work accomplished and often, scientific publications and/or reports.

Cooperative agreements—(for NASA these are also known as Space Act Agreements)-Most commonly used to authorize work in which a non-NASA entity will use NASA capabilities and/or work cooperatively with NASA. References exist for the NASA definition of Space Acts and should be reviewed. This is not a replacement for an Announcement of

Opportunity (AO) or Request for Proposal (RFP) and cannot be used for the delivery of goods or services to NASA.

Directed Developments/Missions—Commonly used for developments in which the core of the work is focused in an organization with a special capability required for the work. Often the goals of the work are very broadly stated in the beginning and multiple stages of study and preliminary development are used to define the work in greater detail. Often, such development efforts will use Announcements of Opportunity or Requests for Proposal for deliverable items or services that become part of the overarching work. Examples are the James Webb Space Telescope Program or the Space Launch System Program.

Announcements of Opportunity (AO)—Competitive broad area announcements (BAA's) for which any person or organization with capability to execute the solicited activity can propose. This includes NASA Centers, Federally Funded Research and Development Centers (FFRDCs), University Affiliated Research Centers (UARCs), Academic institutions, industry, etc. The solicitation is of a general nature, for example, propose instruments, which can be used to achieve the scientific goals of a named mission, scientific missions to address a range of objectives, or technology related proposals to meet a specific or general technological challenge.

Request for Proposal (RFP)—Used for delivery of goods and/or services. The end items must meet a defined specification. A Statement of Work is used to define activities that must be executed in the development of the end items or delivery of services. NASA Centers, FFRDC's, and UARCs cannot generally respond to RFP's but can and do join industry-led teams to do so where consistent with their charters and policies.

Requirements from other documents invoked on programs and Projects via NASA 7120.5 (current versions are available at http://nodis3.gsfc.nasa.gov)

1. Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities, OMB Circular No. A-119.
2. NPD 1001.0, NASA Strategic Plan.
3. NPD 1200.1, NASA Internal Control.
4. NPD 1210.2, NASA Surveys, Audits, and Reviews Policy.
5. NPR 7120.10, Technical Standards for NASA Programs and Projects.
6. NPR 7123.1, NASA Systems Engineering Processes and Requirements.
7. NPR 8705.4, Risk Classification for NASA Payloads.
8. NPR 8715.3, NASA General Safety Program Requirements.
9. NPR 8900.1, Health and Medical Requirements for Human Space Exploration.
10. NASA-STD-8709.20, Management of Safety and Mission Assurance Technical Authority (SMATA) Requirements.
11. ANSI/EIA-748, Standard for Earned Value Management Systems.

Summary

While the discussion above is built around NASA projects and requirements and includes many items unique to NASA and/or levied on NASA and its projects by its stakeholders, others may be useful to people engaged in other work and even non-space-related projects.

The phased life cycle and iteration at successively greater detail is a classic waterfall method used in many large developments. An architect and their customers working on a large one-of-a-kind project would find the logical flow of events and the inclusive, successive decision making leading from needs and goals to detail design and then construction and inspection very familiar. While seemingly antithetical to agile methods, many of the products and risk management information could be useful as references for a team using agile or other highly iterative methods but also needing to coordinate outside of the local domain in which the agile methods are being employed.

While the materials discussed in this chapter are "requirements," they are also a set of options and required decisions to assemble a plan for a project. Failure to decide is a decision and failure to have a plan is a plan for failure. For every decision there are risks avoided, risks accepted, costs of implementation, and opportunity costs. Making thoughtful, informed choices and open and frequent communication with the stakeholders are the keys to planning for success.

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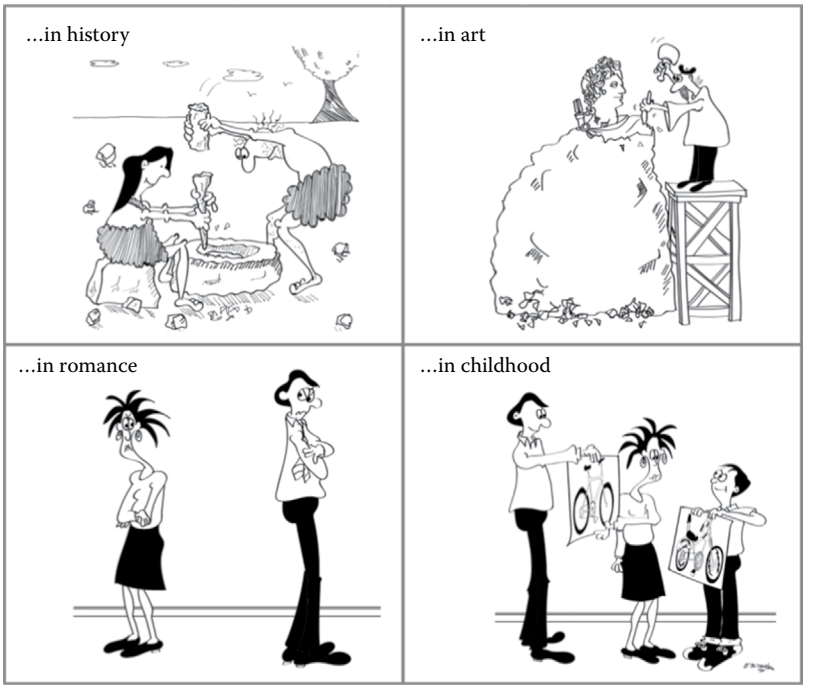
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Section III

Aerospace Project Technical Implementation Topics

Project Management—Phase B (Definition) Reviews:
System Requirements, Systems Design, Nonadvocate




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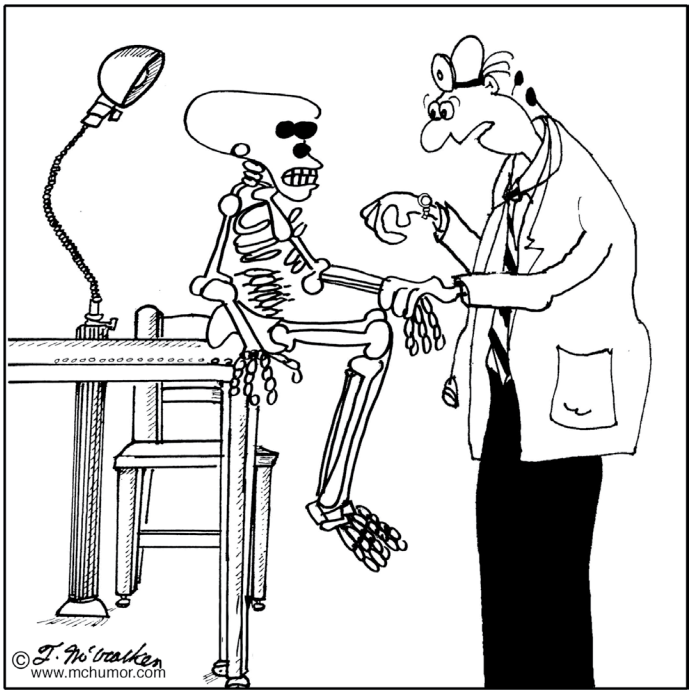
10

Systems Engineering (From the Perspective of a Project Manager)

Kenneth E. Hibbard

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Locking down requirements
later in the life cycle

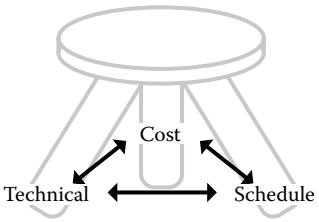


FIGURE 10.1
Successful project management balances the technical capabilities with available resources, specifically cost and schedule.

Introduction

Space projects span a wide variety of efforts, ranging from systems-of-systems to fast, complex missions for the Department of Defense (DoD), to inexpensive sounding rockets, to highly complex, long-duration, deep-space missions. Systems engineering is the only reliable and traceable means sanctioned by the aerospace industry to manage the development and implementation of large projects.

To accomplish these varying goals, many organizations codify systems engineering practices into processes, rules, design principles, and quality standards. These are often tailorable for each project to permit flexibility to accommodate specific objectives within available resources and relative to agreed-upon, acceptable risk.

An aerospace project manager (PM) does not require an intimate knowledge of systems engineering, exactly what it is, or how it is performed. So the obvious question is why should a PM care about systems engineering, and why is it important to them? Fundamentally, an aerospace PM must balance the technical effort against the allocated schedule and available costs. For a project to be successful, these three primary factors must remain balanced, much like the legs of a stool as shown in Figure 10.1; the technical scope must be commensurate with the cost and schedule resources, or vice versa. These control functions are part of project management, yet it is the systems engineer to whom technical authority is typically delegated, owns key trades, and controls the scope of the technical elements [1].

The application of systems engineering standards and practices must strike a balance between ensuring a consistent process and supporting the need for project flexibility and creativity. The unique nature of each project requires an approach that can adapt itself to mission-specific needs. Nonetheless, years of systems engineering practice have yielded guiding principles that can be applied to all hardware and software development activities. This chapter carefully selects the systems engineering processes (requirements development, design specification, performance verification, risk management, technical coordination, and documentation) that are deemed critical to project success and application to space projects.

Roles and Responsibilities: The Many Layers of Systems Engineering

Systems engineering is the responsibility of all engineers, scientists, and managers working on a technical development project since each shares part of the overall systems engineering effort. This section outlines the roles and responsibilities of key project staff that

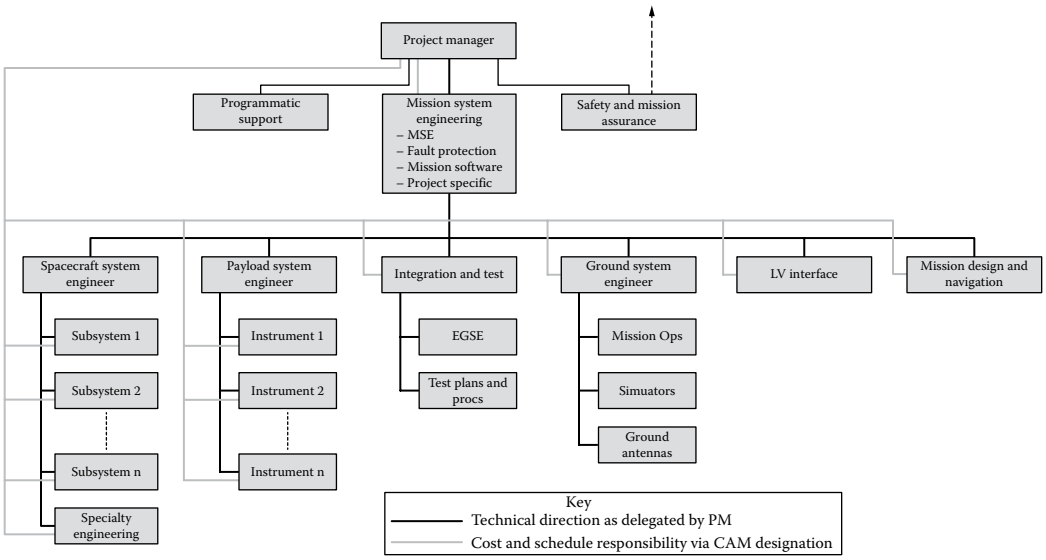


FIGURE 10.2
Typical large project organizational physical structure showing both technical and programmatic lines of authority.

form the systems engineering team. These expectations are expressed in the context of the baseline technical decision-making structure shown in Figure 10.2. Individual project structures are adapted to each project's unique size and needs. Each project is responsible for parsing systems engineering roles and responsibilities into the project organization and documenting the result in the systems engineering management plan (SEMP).

Figure 10.2 also depicts the hierarchical nature of the design, flowing down from the mission level to segments, subsystems, and finally components. As Figure 10.2 shows, the mission systems engineer (MSE), supported by any necessary technical experts, leads the technical team performing the development and integration of the project segments. Depending on the complexity of the project and the allocation and delegation of responsibilities, some functions may require multiple people while others may be handled by one person on a part-time basis.

A "subsystem" can represent a variety of elements, including a hardware element (such as an integrated electronics module), a combined hardware and software element (such as an attitude control subsystem), a software element (such as satellite command and control software), or even a function that crosses multiple hardware and software elements (such as fault protection). The definition of subsystems will vary from project to project, so the SEMP must identify the subsystems for each project.

The following describes the roles and responsibilities of project team members with direct systems engineering responsibility. It is not a comprehensive list of the functions and responsibilities of these team members, but rather the significant roles each has in implementing systems engineering standards.

The MSE, as shown in Figure 10.3, heads the systems engineering team and acts as the ultimate technical authority on a project, reporting to the project manager. This position is sometimes referred to as the project systems engineer. The MSE bears the ultimate responsibility for the technical performance of the mission and all of its segments. On complex projects, more than one person may be needed to fulfill the responsibilities

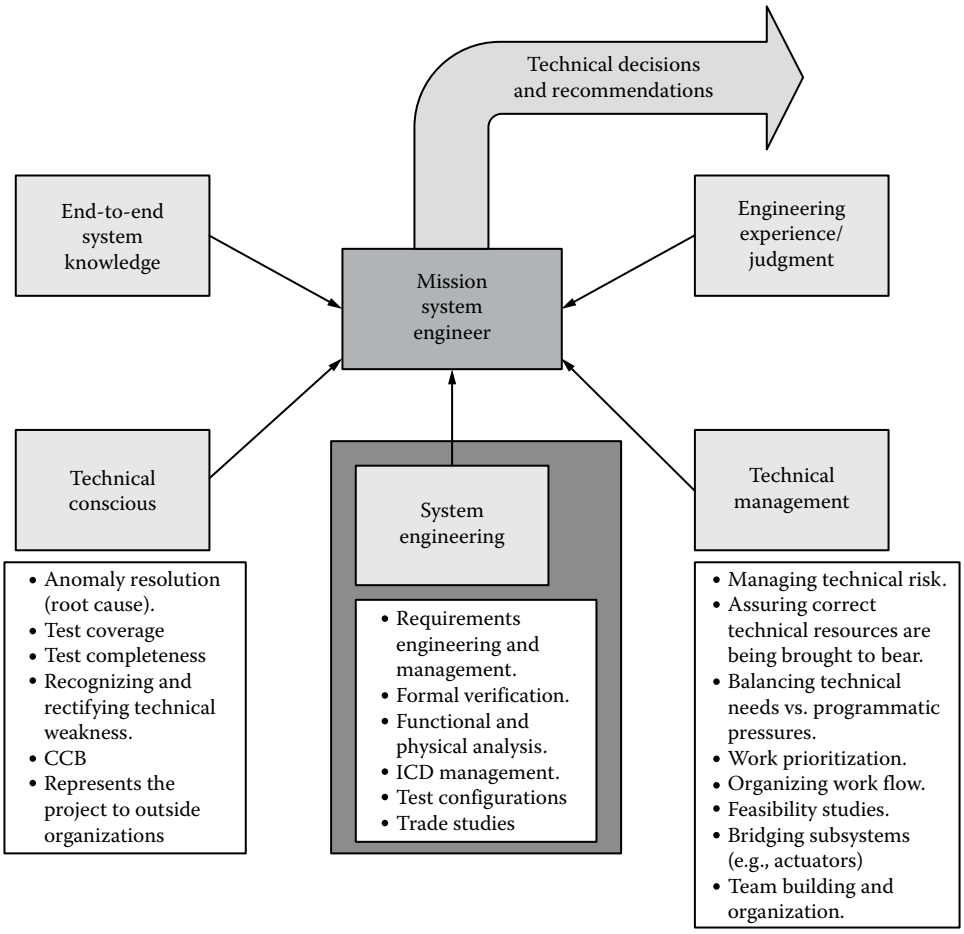


FIGURE 10.3
Skills and capabilities utilized in mission systems engineering role.

listed here for the MSE. The responsibilities and workload are delegated appropriately among members of the systems team.

The major responsibilities of the MSE include:

- Develop the mission requirements documentation. This includes flowing down of mission-level requirements to the major mission elements (spacecraft, payload, mission operations, and ground system). The MSE also provides oversight of all of the mission segment requirements, specifications, and requirements for major system components and subsystems, and develops and documents a mission concept of operations that outlines the system architecture, major interfaces, and strategy for deployment, operations, and disposal.
- Perform system-level trade studies and document the results. Key project staff, particularly the segment system engineers and the systems assurance manager (SAM), supports mission-level technical oversight. The MSE must ensure that trade studies are identified, performed, evaluated, and documented in a manner that supports timely recommendations for the development effort.

- Develop interface control documents (ICDs) among major mission elements (spacecraft, payload, ground components, operational elements, and launch systems) that satisfy requirements and constraints.
- Establish the mission software development plan, although this is typically delegated to the mission system software engineer. The software development plan describes the development approach and technical standards to be applied to all flight, ground, and test software used in the project. This effort recognizes the increasingly critical role played by software in modern spacecraft and ground systems.
- Develop the system verification plan to ensure a comprehensive process that leads to end-to-end verification of mission requirements. Provide oversight to ensure that the system verification plan requirements flow into all integration and test (I&T) plans, including the spacecraft, payload, ground system, and operations capabilities and readiness.
- Develop and maintain a risk management database for the project office. Maintaining global oversight of the technical development is critical in being able to identify and analyze risk exposure and consequences. Formal risk identification processes include the development of failure modes and effects analysis (FMEA), fault tree analysis (FTA), and probabilistic risk assessment (PRA) with the support of the larger systems team. The MSE ensures that resources are applied to develop risk mitigation plans in addition to tracking actions and progress related to risks, and resolves risks within the technical development area and provides recommendations to the project office regarding potential impacts when appropriate.
- Establish the specific resource allocations and performance requirements for design margins; ensure that margins are tracked and trended throughout the technical development and that they are consistent with organizational margin guidelines.
- Establish and maintain a history of significant mission requirement and design changes and the impacts of those changes.
- Provide regular systems engineering status updates to the program/project office.
- Serve as a primary technical interface with the sponsor and the sponsor's oversight team.
- Organize major system reviews.
- Track action items (AIs) and ensure their timely resolution and closure.
- Provide to the project manager certification of mission readiness to launch.
- Ensure the creation of a product tree for the system to facilitate development and maintenance.

To carry out these responsibilities, the MSE relies heavily on the mission system engineering team:

Segment system engineers for each of the major mission segments—spacecraft, payload, ground systems, mission operations, and payload (science) operations.

Integration and test engineer ensures that the mission development includes requirements and features to support integration and testing and coordinates the flow and the development of test procedures to verify all testable requirements.

Mission system software engineer oversees the project's software development efforts; more detailed description in the following text.

Mission [trajectory] designer supports the MSE and project staff with analysis and data products required to perform trade studies and establish the launch, orbit, and trajectory/maneuver design parameters and requirements.

Fault management engineer coordinates the system-level definition of requirements and capabilities necessary to implement the mission fault tolerance and the fault recovery architecture for the mission; oversees the design, implementation, and testing of the system features that satisfy these requirements across the various mission segments.

System assurance manager (SAM) is responsible for assuring design guidelines, processes, and requirements are established by the mission requirements, which includes sponsor risk tolerance and organizational quality management policy; documents and clearly communicates the quality assurance requirements and procedures to the development team and incorporates them into all aspects of the mission; and tracks anomalies as well as problem/failure reports (P/FRs). The SAM also assures that configuration control is maintained, that EEE (electrical, electronic, and electromechanical) parts are consistent with specified requirements and de-rating criteria, and that processes and materials are compatible with the requirements for electromagnetic interference and compatibility (EMI/EMC), contamination control, lifetime, and safety. The SAM is responsible for procurements being executed with all applicable flight assurance requirements (flow down of requirements to subcontractors and suppliers), and that all flight software meets organizational software quality assurance requirements.

Reliability engineer supports the MSE by performing the reliability-focused tasks of FTA, FMEA, and PRA.

Specialty engineering supports various unique engineering design, evaluation, and verification needs of the mission. These include, but are not limited to, EMI/EMC, contamination control, and radiation effects.

The *spacecraft systems engineer (SSE)* is responsible for developing and managing the spacecraft design. The requirements are nearly identical to those of the mission system engineering team, except that the scope is limited to the spacecraft. Because the spacecraft bus represents much of the mission complexity, the spacecraft bus and mission system engineering teams work together closely to ensure mission success.

The SSE is responsible for managing and controlling the technical development of the spacecraft bus segment of the mission, with the support of the team of lead engineers responsible for specific spacecraft subsystems and of the software engineers, integration and test engineers, and specialty engineering staff (EMI/EMC, contamination, etc.). The SSE delegates areas of responsibility within the spacecraft systems team.

The major responsibilities of the SSE include the following:

- Develop the spacecraft-level requirements documentation and flow spacecraft-level requirements down to the subsystem elements. A key element of this requirements flow down is identifying any new requirements to flow back to the mission level, along with identification of trade studies required at the mission level, to support spacecraft implementation decisions.
- Oversee the development of spacecraft system documentation, including the review and approval of the specifications for all subsystems, principal components, and mission-specific ground test equipment.

- Develop and maintain ICDs or equivalent system drawings that document spacecraft component interfaces such as implementation-specific electrical interfaces, grounding test interfaces, mechanical interfaces, thermal interfaces, and assembly drawings as well as hardware/software interface documentation including ground support equipment (GSE).
- Establish spacecraft component environmental design requirements enveloping worst-case predicted analyses of the mission and ground processing environments; document and maintain requirements as they mature, including the required design and test margins.
- Support the project risk management process by monitoring the spacecraft development and identifying areas of technical performance risk, schedule risk, and cost risk; develop and document an FMEA for the spacecraft that, at a minimum, covers the functional and interface level.
- Manage spacecraft resources through allocation, tracking, and margin management processes.
- Ensure that the objectives of the formal review and peer review processes are satisfied for each of the spacecraft subsystems, including both hardware and software designs elements.
- Provide the oversight to ensure that configuration management processes are followed for subsystem specifications, ICDs, spacecraft system drawings, test plans, problem reports and resolution, waiver processes, etc., related to the spacecraft and associated GSE.
- Provide oversight of the integration, test, and verification process for the spacecraft segment. Oversee the development and review of spacecraft test procedures to ensure comprehensive test coverage and coordinate the systems review of all spacecraft test processes and test results, including the disposition of all spacecraft and associated GSE failures and anomalies.
- Provide to the MSE certification of spacecraft readiness to launch. The SSE must obtain certifications of readiness from the spacecraft subsystem leads in support of this.

As shown in Figure 10.4, to carry out these responsibilities, the SSE relies heavily on both mechanical and electrical systems engineering leads:

Mechanical system engineering coordinates among the structural analysis, mechanical packaging, thermal engineering, propulsion engineering, and guidance and control functions.

Electrical system engineering coordinates among the flight avionics, telecommunications, power, and harnessing functions.

While Figure 10.2 shows a typical physical structure, Figure 10.4 exemplifies how systems engineering deliberately uses distributed services, requiring robust and distinct leadership. The existence of a function does not necessitate that a different person perform that role, but rather staffing is defined per each unique project to allow for higher levels of efficiency. In general, functions should be staffed to facilitate direct interaction with the work being performed, handle problems at the lowest possible level, allow for a significantly lighter systems engineering organization at the top levels, and to provide a common framework throughout the project organization.

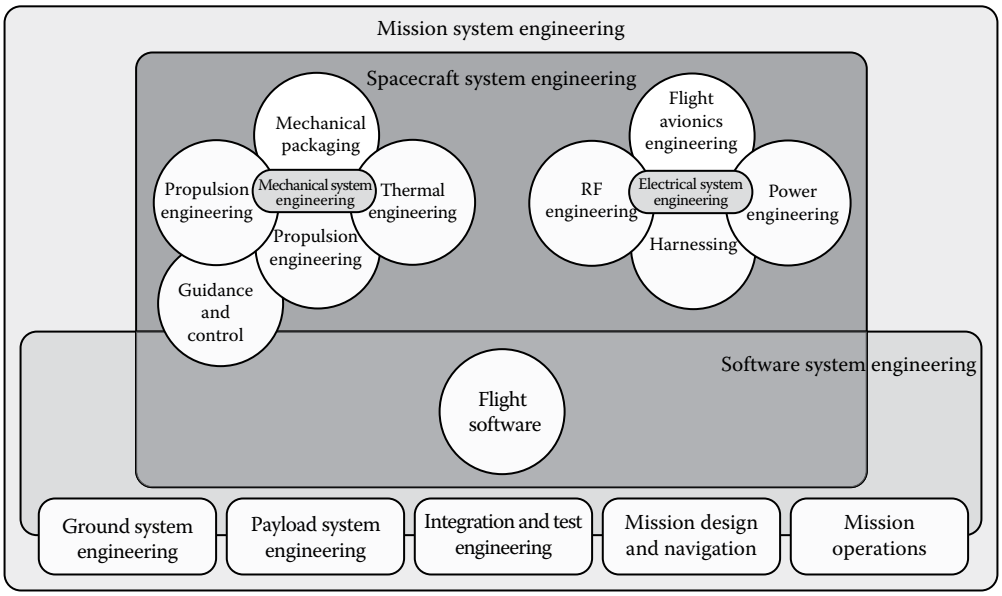


FIGURE 10.4
Typical large project organizational functional structure showing SSE functions broken out.

Mission software systems engineer (MSSE) supports the MSE, the project manager, and the SAM; develops and maintains the software development plan; establishes criticality levels for each major software component; provides oversight and support to all software development efforts. Mission- and segment-level software system engineers, who coordinate software development activities across the project, typically back up the MSSE. Segments that include software elements in deliverable systems or critical test items will have a segment system software engineer or a lead software engineer supporting the organizational system design standards.

Payload Systems Engineer (PSE): For payloads developed within the same organization as that managing the mission and/or providing the spacecraft, the responsibilities of the payload (instrument) system engineering team are similar to those of the MSE and SSE. For payloads provided by external institutes, the managing organization sometimes provides systems engineering support to the payload team. The PSE manages and controls the technical development of the payload segment. They coordinate the payload development process; serve as the technical interface between the payload development teams and the broader mission and spacecraft system engineering teams; and act as an advocate for the payload.

Ground System Lead Engineer (GSLE): The GSLE manages and controls the technical development of the ground system segment. The GSLE coordinates development and implementation of the ground mission assets, including software systems, which may include the mission operations center (MOC), payload operations center (POC), communications networks, ground station(s), and GSE data system. The GSLE acts as the technical interface between the ground system team(s) and the rest of the mission and spacecraft systems engineering teams. The GSLE works with the MSE, SSE, PSE, and software systems engineer to develop the ground system ICDs, which will include, at a minimum, a ground system-to-spacecraft ICD. The GSLE is responsible for developing internal ICDs, which may include MOC-to-mission planning interfaces, MOC-to-ground station

interfaces, ground network interfaces, ground support test interfaces, as well as project service-level agreements with government agencies.

Mission Operations Manager (MOM): Although the mission operations function does not produce a physical product, it follows the same systems engineering process used for other segments. The mission operations team develops a mission operations plan consistent with the requirements flowed down by the mission system engineering team. The operational requirements are tightly coupled with the spacecraft and ground system requirements. The MOM is responsible for managing and controlling the technical development of the procedures and processes required to successfully deploy, commission, and operate the mission after launch, including data acquisition and distribution. The MOM coordinates the development of operational procedures, process controls, and staff expertise. Finally, the MOM works with the project system engineers to ensure that the design process adequately considers operability issues.

Payload Operations Manager (POM): The payload (science) operations team is responsible for applying systems engineering processes to develop systems and capabilities that provide payload data products and that support the payload operations requirements. On some projects, this function is combined with the mission operations team. The POM is responsible for managing and controlling the technical development of the procedures and processes required for successfully deploying, commissioning, and operating the payload after launch. The POM coordinates the development of operational procedures, process controls, and staff expertise.

Launch Vehicle Lead Engineer (LVLE): Launch vehicle systems engineering is performed by the launch service provider and is not typically subjected to the technical oversight of the mission system engineering team. However, a mission systems team member (the LVLE) is responsible for ensuring that launch vehicle considerations and interfaces are coordinated between the mission development team and the launch vehicle contractor.

Systems Engineering Management

Technical Management and Oversight: The role of systems engineering is as much a management job as a technical one. Technical management and monitoring consume the greatest percentage of a system engineer's time, yet it is nearly impossible to codify requirements for this aspect of the systems engineering function. Figure 10.5 shows systems engineering in the context of overall project management per the *NASA Systems Engineering Handbook* (NASA/SP-2007-6105 Rev 1), as these two major roles go hand-in-hand with each other.

One essential technical management role is facilitating the flow of technical communication among the project team members. Since almost every element of the system interacts with every other element to some degree, the success of systems engineering depends on all team members understanding how their system element fits into the larger mission design. The systems engineering process, represented in the project-level systems engineering life cycle in Figure 10.6, relies heavily on the systems perspective of the many experts supporting the development to identify the many assumptions and design decisions that may affect other elements of the system. This flow-up of information is necessary for well-informed system trades and design decisions. While the dynamics of any

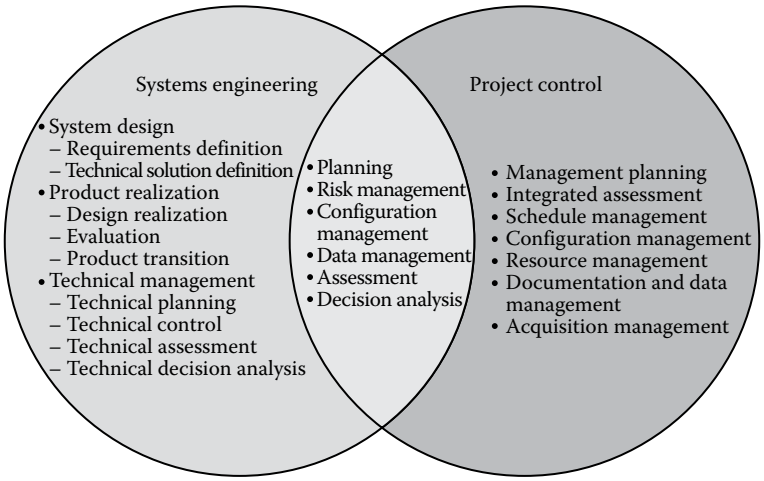


FIGURE 10.5
SE in context of overall project management. (Data from NASA, *Systems Engineering Handbook*, Revision 1, National Aeronautics and Space Administration (NASA), NASA/SP-2007-6105, Washington, DC, 2007.)

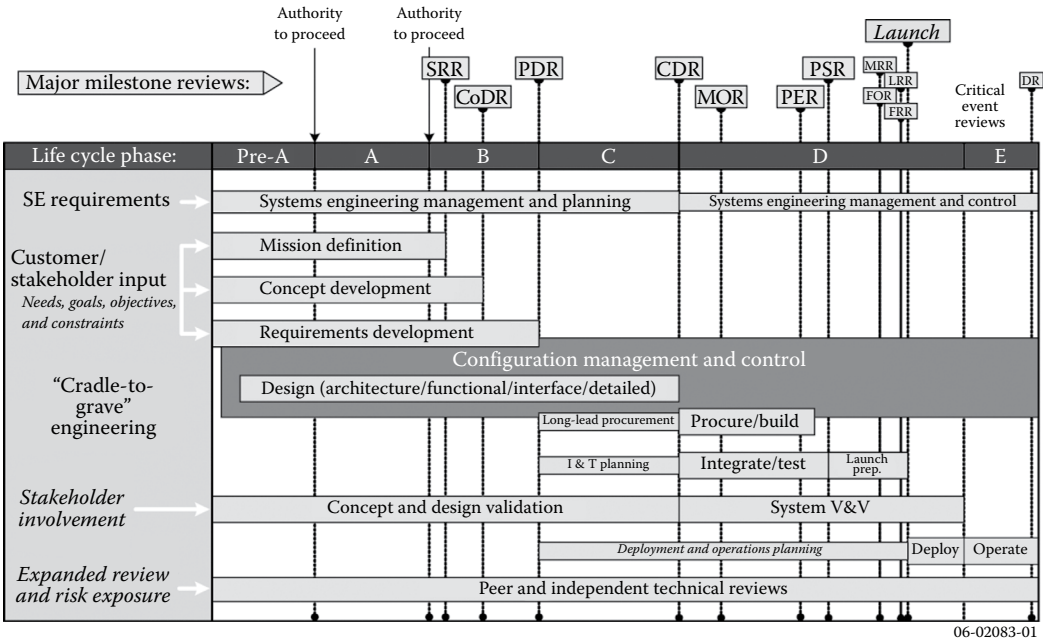


FIGURE 10.6
Historical life-cycle systems engineering is a product-driven, gated process designed to provide greater risk visibility. This process, compliant with NPR 7120.5E, is tailored on a mission-by-mission basis.

particular team will depend on its individuals, the system engineers must develop a team that is involved in system design by fostering open communication and demonstrating responsiveness to issues brought forward by members of the team.

Another primary element of the technical management role is participation in elements of the detailed design when significant technical problems or issues arise. In some cases, the system engineer may be able to lend expertise to the issue at hand. Regardless, systems engineering involvement is needed to determine if a system solution can be employed. This decision can involve a reallocation of system resources, functional reallocations, and modification of requirements, or relief from requirements. Once a potential solution is identified, the system engineering team must ensure that its system impacts are understood.

The oversight role is performed by attending system and subsystem design meetings, reviewing documentation, and participating in design reviews. The system engineering team is responsible for ensuring that the technical design process is consistent with the requirements of the particular development organization and its design standards.

Systems Engineering Management Plan (SEMP): One of the first tasks of the MSE is to establish the SEMP. The SEMP describes, accurately and in detail, the systems engineering-related roles and responsibilities of each project team member. At a minimum, the SEMP must address all of the required elements of an organization's systems engineering standards. For projects with a scope smaller than full mission implementation responsibility, the SEMP details the extent to which these standards apply to that project. A draft SEMP is required at the project's system requirements review (SRR), and the final version should be delivered by the concept design review (CoDR) and signed off by the organization's chief engineer.

Primary Technical Interface: Systems engineering, specifically the MSE, serves as the primary technical interface of the project, both internally and externally. They will work in close collaboration with the sponsor/sponsoring organization, any external providers, and any partner organizations that interface to the project to ensure appropriate technical information is effectively communicated. Many of these interactions are performed in partnership with the PM, as the technical status and well-being of a project cannot be expressed without the appropriate context of project resources, and vice versa.

Technical Authority and Review: It should be noted that ultimate technical authority remains with the PM, who in conjunction with the sponsor owns the project risks and resources. Systems engineering authority is often delegated from the PM to make day-to-day technical decisions and assess trade-studies that are made within the larger programmatic bounds. For technical decisions that will significantly impact the project or require additional resources, the SE makes recommendations to the PM; the SE has a large say in these matters, but not the final word. An independent technical review should be executed by the developing organization, often via a chief engineering office, and is typically implemented via the project's peer review process. On many teams, an independent review team or standing review board (SRB) is chartered by the sponsor organization to provide another independent assessment at major gates and milestones. It is highly recommended to offer a separate path outside of the project's structure to raise any issues, concerns, and adjudicate any significant technical disconnects helping ensure project success.

Risk Management: Although the PM is responsible for the risk management process, the MSE and the rest of the system engineering team is integral to the process. The MSE leads many of the formal risk management activities, such as fault tree analysis (FTA), failure modes and effects analysis (FMEA), probabilistic risk analysis (PRA), margin management, and preparation for design reviews, to name just a few. For all risks, the system

engineering team evaluates the system impact of risks and proposed mitigation techniques and advises the PM on risk management issues. On some projects, the PM may delegate additional risk management responsibilities to the MSE, including drafting the risk management plan and managing the risk management database and risk watch list.

Independent Reviews: An independent review process is typically required, and strongly encouraged, for all space projects. For projects where the end deliverable is a subsystem, instrument, or component, the project lead technical authority shall assume the MSE responsibilities described here.

The independent review process employs three levels of technical reviews: system, subsystem/instrument, and peer. A typical phased review approach during the mission life cycle is shown in Figure 10.7, highlighting these various review levels. The MSE shall work with the PM to establish the mission review plan. This plan defines the subsystems to be reviewed and the number and timing of subsystem design reviews and peer reviews. The review plan is tailored to each project based on its unique needs, challenges, and scope. The review plan shall be documented in the project plan or the SEMP. Engineering peer reviews are the critical cornerstone of the review process. Their intent is to get in-depth feedback on specific designs and aspects of this mission. These reviews are held at the engineering level and contain significant design content; design documents, analyses, drawings, flow diagrams, code, hardware description language (HDL), schematics, etc., often take the place of view graphs. Peer reviews employ area experts in an attempt to apply diverse experiences and assure design robustness. Peer reviews still require review packages, AIs, and minutes. It is also highly encouraged to utilize at least one member of

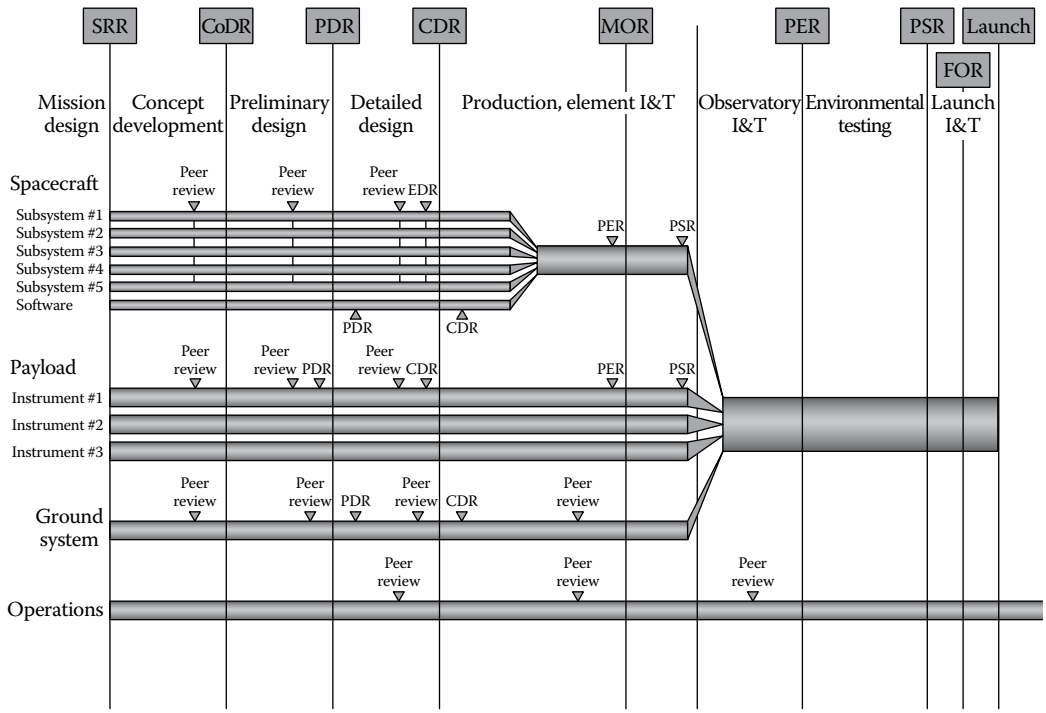


FIGURE 10.7
Review phasing throughout a typical mission life cycle.

the SRB, and a reviewer who is independent of the project team and the development organization. The MSE plays a key role in AI management. In many cases, the MSE or a deputy is responsible for managing the AI database and reporting the AI status to the project management. At a minimum, the MSE should review the AI database and ensure that AIs are being closed out in a timely fashion.

Systems Engineering Documentation: As the technical leader of the project, the MSE is responsible for developing all necessary technical documentation, including those generated by the mission system engineering team and the segment system engineering staff. To help in the management of the required systems engineering documentation, the MSE should create a document release schedule based on the requirements of the specific project sponsor (e.g., NASA documentation requirements and deliverables are specified in NPR 7123.1B). The release schedule lists each system engineering document and its scheduled release date. The record also tracks the current planned release date. A list is a useful tool for identifying areas where the development effort may be getting off track and needs additional attention.

The specific documents required on a project will be specified in project documentation such as the project plan, the system engineering management plan, etc.

Like the system itself, the documents required for systems engineering follow a hierarchy from the mission system level to the segment level. For example, a mission-level requirement document is designed to take the top-level mission requirements and flow them down to the mission segments. This process is repeated at the payload, spacecraft, ground station, and operations levels. Some documents (such as the risk management plan and software development plan) may be written so that a single document can apply to all mission segments and levels. The decision of how to manage the documentation requirements lies with the MSE in coordination with the PM.

Technical Margins and Resource Management

Every organization must establish standards for defining, computing, selecting, and managing system resources and margins. For this book, system margins are defined as those resources and design parameters that impact system-level requirements, substantially affect multiple system segments or subsystems, or significantly impact system risk. These guidelines are provided by risk management for nominal missions.

System margins are an essential risk management tool. Two categories of margin are considered, resource margin and design margin. Resource margins allow the project to be very robust on the unexpected hurdles encountered during system development. Design margins ensure that the design will be robust in the presence of design errors (models and worst-case analysis), uncertainty in implementation variables (electronic noise, contamination, design changes), and environmental prediction uncertainty. On the other hand, excessive margins drive a system to be more complicated and expensive than necessary to perform the given mission. Determining trade-off details is part of the systems engineering process on each mission. The margin assessment process suggested here reflects the relationship between margin levels and development risk associated with the resource. Resources with greater uncertainty or growth risk carry commensurately higher margin levels. Furthermore, the desired resource margin decreases as the project progresses, because as the design matures the likelihood and extent of expected growth is reduced.

By linking margins to risk, some projects may elect to adopt more stringent guidelines as a result of mission-specific risk factors. Similarly, projects may operate with some margins that are below typical levels. Margins below defined minimum levels (as detailed in the project's SEMP) should be tracked as a risk project item. While it may be entirely appropriate to use lower margins for a particular resource, it is important that this decision receives proper scrutiny and visibility to ensure that it does not adversely affect the project risk.

Allocated and Unallocated Margin: To manage margin based on knowledge of uncertainty and risk, the margin is sometimes split into allocated and unallocated margin. Allocated margin is the margin given to a subsystem or unit to account for the risk of growth in that subsystem and is referred to as "contingency" or "reserve." The level of margin allocated to a particular unit or subsystem should be based upon the maturity of that system, as shown in Table 10.1. This value is added to the current best estimate (CBE), or proposed value, to get a maximum expected value (MEV). Unallocated margin is the margin owned by the system engineering team and is the difference between the maximum expected value and the maximum possible value (e.g., launch vehicle lift mass). This margin is distributed to subsystem engineers on an as-needed basis to cover significant unanticipated problems encountered during the project. For this reason, the project must maintain a positive unallocated margin for all parameters at all times.

Resource Control and Tracking: The MSE bears ultimate responsibility for all system budgets. System budgets consist of contributions from multiple subsystems. Mass and power are two obvious examples, but attitude control is also a system budget. It includes attitude sensors and actuators, time management, mechanical alignments, and thermal distortion.

Some resources allow performance to be measured in a common manner (mass, power, data), and these resources lend themselves to simple qualitative allocation and management. Others (pointing budgets, ΔV, and navigation) depend on a number of diverse variables that do not necessarily have a common performance measure and may be statistical in nature. These resources and performance measures are tracked by developing a tree-structured budget that establishes the relationships between measurable or analytical performance variables and the specific margin. For example, the pointing knowledge of an instrument may be based on sensor accuracy, sensor update rate, sensor-to-instrument mechanical alignment, thermal distortion, and finally the sensor calibration.

Table 10.2 identifies system margins and management methods. Margins shown in bold type are recommended for all space projects. Other margins should be selected for active management depending upon the applicability to the project. If the spacecraft bus is being built under a subcontract, the subcontract statement of work must reflect these margin management and reporting procedures.

TABLE 10.1

Management of Allocated Margin

Maturity of Design	Recommended Allocated Margin (%)
New development	15
Modification of existing design	10
Minor modification of existing design	5
Development unit complete	5
Build to print	5
Measured value	1

TABLE 10.2

System Margins and Recommended Method for Tracking and Reporting

	Tracking/Reporting Method	
System Margin	**Algebraically Computed (Allocation Table)**	**Analytical Contribution (Error Tree)**
Mass	✓	
Power	✓	
Deterministic ΔV	✓	
Nondeterministic ΔV		✓
Propellant	✓	
Attitude knowledge		✓
Attitude control		✓
Alignment		✓
RF link[a] (up and down)	✓	
Data rate	✓	
Payload and engineering data storage	✓	
Data downlink time	✓	
Critical CPU time[b]	✓	
Critical processor memory[b]	✓	
Critical nonvolatile memory[b]	✓	
Data bus throughput[b]	✓	
Position, velocity knowledge		✓
Time knowledge	✓	

Note: Margins listed in bold type are required for all applicable programs.

[a] Link margin is expressed in dB.

[b] Expressed as a percentage of unused resources.

Margin Trending: The appropriate level of margin varies with each system resource budget parameter. For each actively managed margin, the system engineering team should maintain a log of the margin. For activities prior to the preliminary design review (PDR), the log should be updated at least quarterly. After PDR, the log should be updated at least bimonthly. The log should also be updated whenever any significant changes occur, along with an annotation of the reason for the change.

Allocated resource margins typically decrease as the design matures and resources are utilized. Margins based on error analysis, such as pointing errors, typically increase with time, because the error sources are typically based on not-to-exceed values, many of which should become less uncertain as the design matures. Tables 10.3 and 10.4 show commonly assigned margins to mass and power, respectively, as examples and how these decrease with a maturing design. Note that total margin is the sum of contingency, or allocated margin, with unallocated margin.

Subsystem Margins: Subsystem margins also play a key role in the project risk management process. The system engineering team is not responsible for establishing requirements or managing these margins; however, the project system engineers should be cognizant of the subsystem and detailed design margins being applied. In particular, the system engineering team must ensure that subsystem margins are used in all designs and that the selected design margin is both adequate for the design and consistent with the system margin philosophy.

TABLE 10.3

Common Mass Margins

Program Phase	Total Margin (Green, %)	Total Margin (Yellow, %)	Total Margin (Red, %)	Minimum Unallocated Margin (%)
Conceptual design review (CoDR)	≥30	20–30	<20	10
Preliminary design review (PDR)	≥25	15–25	<15	10
Critical design review (CDR)	≥15	10–15	<10	5
Pre–environmental review to launch	≥7	5–7	<5	5
Pre-ship review (PSR)	≥2	1–2	<1	1

TABLE 10.4

Common Power Margins

Program Phase	Total Margin (Green, %)	Total Margin (Yellow, %)	Total Margin (Red, %)	Minimum Unallocated Margin (%)
Conceptual design review (CoDR)	≥30	20–30	<20	10
Preliminary design review (PDR)	≥25	15–25	<15	10
Critical design review (CDR)	≥15	10–15	<10	5
Pre-environmental review to launch	≥10	5–10	<5	5

Total Dose Radiation Design Margins: Every development project for space mission hardware should perform a radiation analysis based on the expected space environment. Unless otherwise defined in an approved performance assurance information package, a radiation design margin of 2.0 is commonly used for evaluating the compatibility of EEE parts with respect to total dose exposure, that is, flight systems shall be designed to a total dose that is double the predicted value.

System Specification and Performance Verification

Many organizations strive to provide cradle-to-grave systems engineering support to their projects, applying basic SE techniques across the mission life cycle through system architecture definition, requirements development, functional and physical descriptions, implementation, verification and validation, and operations. This is fundamentally the application of technical management to control the project baseline and technical resources, as shown in Figure 10.8.

Systems Architecture: Although necessarily a formal SE deliverable, development of the systems architecture is a critical aspect of the early efforts of a project. Systems engineering is responsible for defining the architecture as a means of understanding what interfaces exist and where controls need to be applied. The architecture typically evolves from early trade-studies that include system constraints, risk tolerance, fault tolerance (i.e., redundancy), preexisting elements (e.g., ground networks, other assets available to the project), concept of operations (ConOps), cost, schedule, and so on [2].

Requirements and Requirements Flow Down: Systems engineering is responsible for developing a hierarchical set of requirements based on project needs. Typically, they own

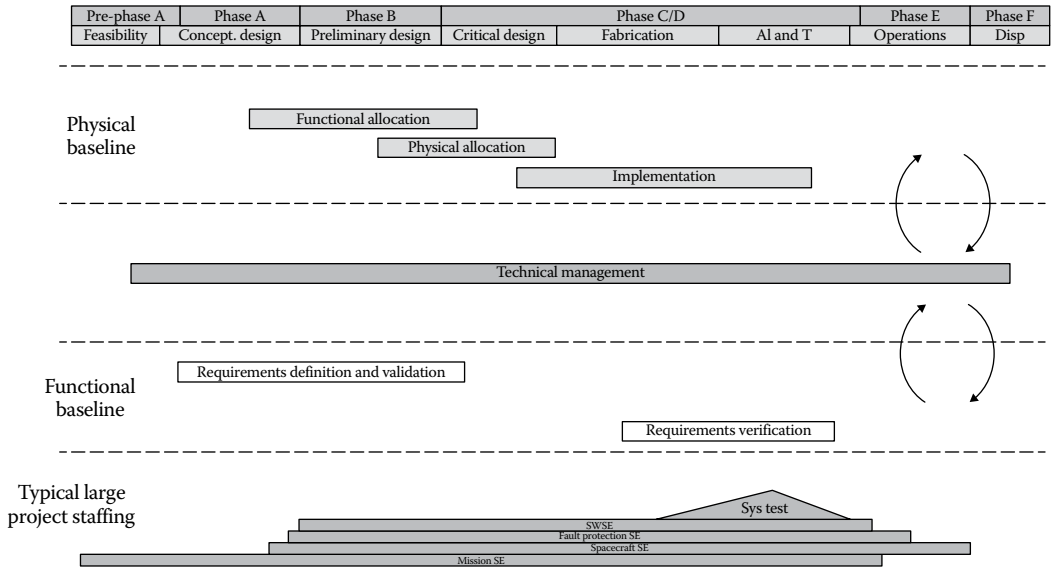


FIGURE 10.8
Cradle-to-grave SE support.

requirements down to (but not including) the subsystem level. Systems engineering is responsible for managing these requirements throughout the life cycle of the project, including developing requirements, requirements validation, allocating requirements (physical and functional analyses), monitoring requirements during implementation, and system-level requirements verification. The plan for performing requirements engineering is captured as part of the SEMP, which may well dictate how requirements are handled at all levels. Many organizations use DOORS® from Telelogic® as the standard tool for managing requirements. Mission design and development starts with requirements definition, decomposition, and allocation. The requirements process is hierarchical; that is, the mission objectives are developed into mission requirements. The mission requirements are then flowed down to each mission segment and then to each subsystem. At the same time, the derivation of requirements at the lower level generates new requirements that flow back up the requirements tree and down to a different subsystem. Requirements may also be imposed on the technical development approach and implementation by the sponsor. The MSE focuses on the flow of mission requirements to and from each segment. The segment system and lead engineers take the mission requirements, flow them down to subsystems, and derive new requirements. The flow down of mission requirements is depicted in Figure 10.9.

Functional Analysis: The requirements flow down process performed by the system engineer shall include functional analysis. The functional analysis results are captured in trade-study documentation and requirements documents. Functions are discrete actions necessary to achieve the system's objectives. These functions may be stated explicitly, or they may be derived from stated requirements. The functions will ultimately be performed or accomplished through use of equipment, personnel, facilities, software, or a combination of these. The process of functional analysis looks at a system in terms of the functions it must perform rather than the hardware and software required to perform those functions. The use of functional analysis helps the system engineer allocate

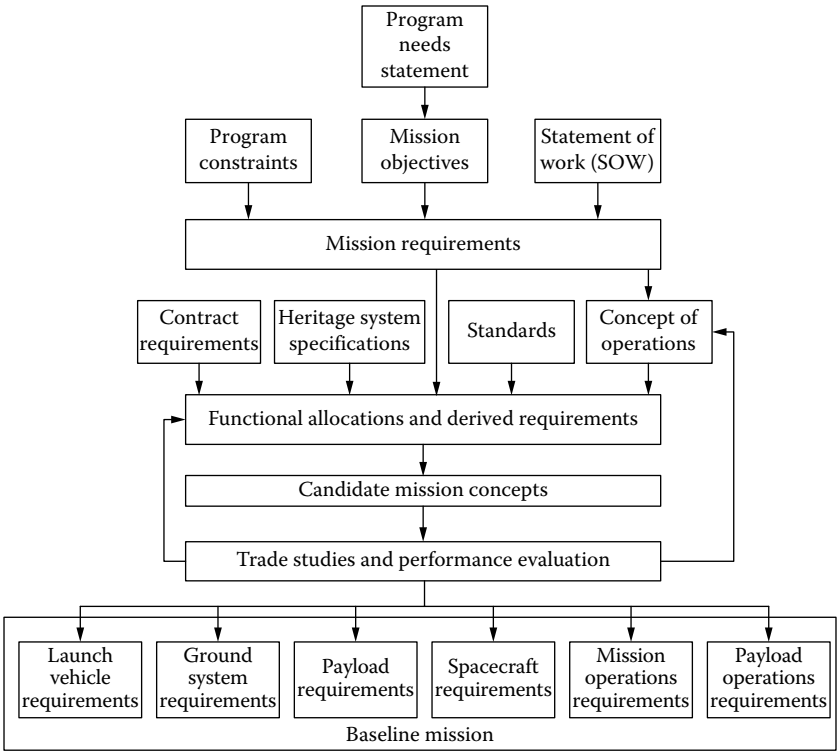


FIGURE 10.9
Hierarchical representation of requirements development tree. (Mission Requirements Flowdown.)

functionality and define interfaces in a manner that simplifies the system design and minimizes the complexity of interfaces. The proper application of functional analysis can have a dramatic impact on the success of the project. Many tools are available to support the development of a functional architecture, such as functional-flow block diagrams (to define task sequences and relationships), IDEF0 (ICAM DEFinition for Function Modeling, where "ICAM" is an acronym for integrated computer-aided manufacturing) diagrams (to define process and data flows), and time sequencing. The end product of these tools is a functional architecture—that is, a description of the system—but in terms of functions and performance parameters, rather than a physical description. Functional analysis and allocation facilitate traceability from requirements to the solution descriptions.

System Specification: The system engineering team is responsible for managing the design process. The first step in this process is ensuring that the design is captured and that all project members are working from a common understanding. This starts with the requirements that are developed at the mission level and flowed down to the subsystem level of each project segment. The Mission Concept of Operation document also captures elements of the design. Finally, each major formal design review provides a complete snapshot of the design at that time. The mission-level design description is baselined by the documentation and actions associated with major reviews. Major system review packages provide an excellent summary of the mission design, which generally changes very little as the mission progresses into the detailed development phase. The mission

requirements, together with the Mission Concept of Operation, are sufficient to provide a top-level understanding of the mission design.

The Mission Concept of Operation document is intended to summarize the mission concept and the overall operations scenario. It describes the end-to-end operation of the system including operational phases, payload operation/observation plans and schedules, ground communications schedule, data management, and other similar aspects of the day-to-day execution of the mission. This document must be developed very early in the project life cycle, since it influences many mission requirements that are not directly derived from the project needs statement or mission objectives. The mission operations plan supersedes the Mission Concept of Operation document as the project matures.

Since the nature of each segment is different, the level of design specification required for each varies as well. For segments developed in-house, the design specification may be captured in a detailed requirements document, the Mission Concept of Operation document, and major design reviews. As a result, spacecraft and payload specification documents are not required, although some projects may adopt them as a valuable means of summarizing the spacecraft or payload design. For procured spacecraft and payloads, a specification is required.

The need for a ground system specification depends upon the degree of requirements documentation at the system level and within the ground system. A ground system specification is required unless an organization is developing the ground system internally and the MSE is maintaining a comprehensive requirements document that specifically defines requirements flow for the ground system.

Mission and payload operations are different from other segments. While the other segments produce tangible products, the mission and payload operation teams primarily provide a service. These segments must clearly identify what services they will provide, and they must help the ground system segment engineers define the necessary system interfaces. They shall produce the equivalent of a segment specification in the form of a mission operations plan, payload operations plan, and data management and data analysis plan. These documents, along with essential interface control documents (ICDs) between the MOC, science operations center (SOC), and other operations elements (details below), provide a detailed description of how mission and payload operations will be conducted. This includes information such as staffing plans, training plans, lists of nominal and contingency operation procedures, spacecraft and payload operation scenarios, contact scheduling, ground system maintenance, and other operational policies and procedures. The precise content of these plans is tailored to the project-specific operational requirements to ensure sufficient definition of the ground requirements.

The requirements documents flow mission requirements to the subsystem level. From this point down, the design is captured through formal specifications. Specification documents are required for all spacecraft subsystems and major components. For mission and payload operations, operation procedures are required rather than subsystem specifications. Formal, documented, verified, and rehearsed nominal and contingency operation procedures are essential to providing a reliable operation service. Operation procedures are required for all nominal spacecraft and payload commanding and for key contingency situations such as a failure to acquire the spacecraft on a scheduled contact. Formal procedures are also highly recommended for routine ground operation tasks that do not involve spacecraft commanding. This is especially true for long-duration missions where staff turnover can be expected.

The system specification process must consider the entire project life cycle from development through disposal. With the increasing level of concern about orbital debris, many customers now require the development of a disposal plan. If required, the mission system engineering team develops that plan, which may be included as part of the Mission Concept of Operations document.

Trade Studies: Throughout the system design process, the system engineering team is responsible for leading system-level trade studies. The system engineering team may also participate in key subsystem design trades. At the subsystem level, subsystem lead engineers are responsible for subsystem and component-level trades to ensure that an adequate design is selected. System trades must follow the structured process described here; the level of detail should be tailored to the impact of the design selection. In general, a trade study is commissioned to select the design that best fulfills a set of requirements, or to refine a requirement from a higher level to a lower one, or to help define requirements; a trade study should be conducted if the decision involved has a major impact on performance, functionality, schedule, risk, or budget.

Interface Identification and Control: Systems engineering is often defined as the "glue" that holds a system together. This characterization is embodied by the systems engineer's responsibility for interface definition and control. The systems engineering team creates and optimizes interfaces as part of the functional decomposition process performed early in the design phase. That effort partitions system requirements and capabilities into functional blocks. For spacecraft systems, these blocks generally become subsystems.

The interfaces between major system segments are managed by ICDs. ICDs are also the recommended method to manage interfaces between subsystems within each segment, such as the interface between spacecraft subsystems or between a ground station and the control center. ICDs should cover both hardware and software interfaces, as well as data products such as analysis inputs and products (i.e., mass properties and power dissipation estimates). ICDs should be used any time an interface crosses a major organizational boundary. These boundaries can be between a vendor-supplied system and an in-house component or even between two components produced in different groups within the developing organization. The effort invested in developing ICDs pays substantial returns by ensuring a smooth integration process.

The systems engineering team is responsible for developing ICDs, defining the parties responsible for controlling and maintaining each ICD, identifying the specific control method, and the means and timing of verification of each. The systems engineers have significant latitude in defining what ICDs are required and what interfaces shall be covered in ICDs. ICDs can be single comprehensive documents or they can comprise a set of documents that define specific interfaces such as mechanical, electrical, data, etc. The ICDs to be developed for interfaces between mission segments and between subsystems of the mission segments should be documented in the SEMP. Figure 10.10 shows a sample template for a system specification tree, including the major ICDs.

Configuration Management and Change Tracking: The systems engineering team defines system design baselines, communicates the current baseline to the design team, evaluates proposed changes to the baseline, and manages changes in a controlled manner. Keeping track of a rapidly evolving design is one of the greatest challenges facing the systems engineering team. It requires constant communication to ensure that the entire design team stays "on the same page" between major design reviews. From a formal perspective, design changes are tracked through the configuration control process of the documents used to capture the design: requirement documents, Mission Concept of Operation, ICDs, and subsystem and component specifications. However, these formal documents cannot be

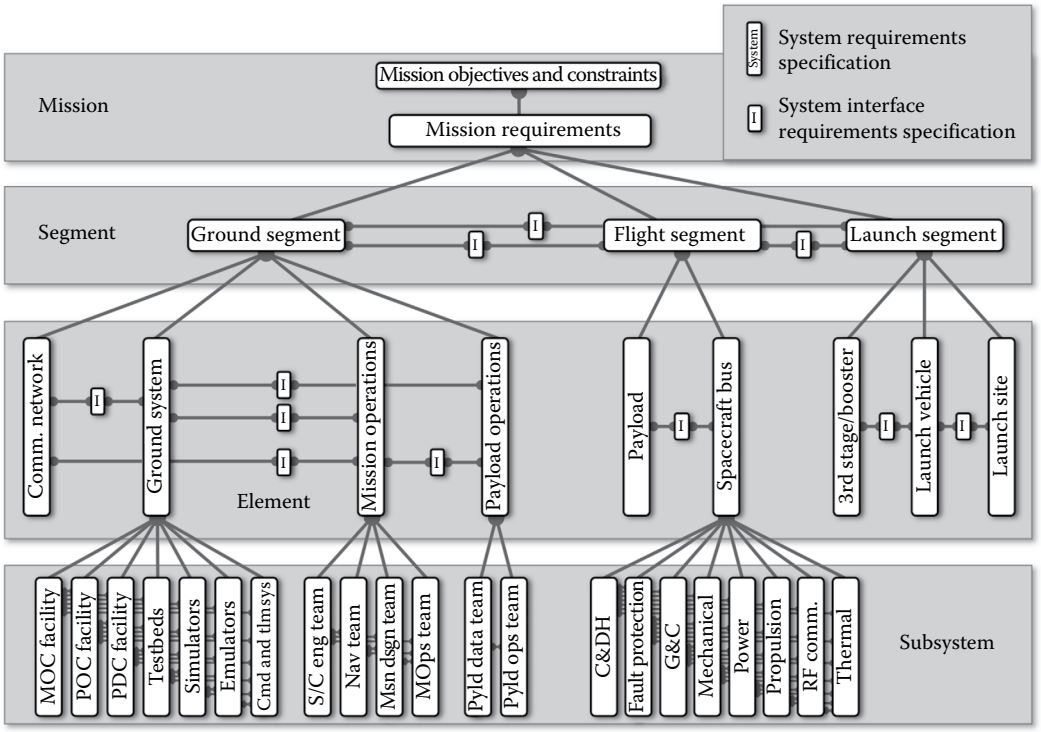


FIGURE 10.10
Sample system requirements specification tree.

updated often enough and quickly enough to maintain coordination of all team members as the design changes. To meet the challenge of constant, effective communication, two of the most powerful tools available to the systems engineer are e-mail and frequent team meetings; informal baselines exist prior to formal control being imposed, capture various design points within the system, and evolve as trades are completed and the design matures between formal baselines being set or updated.

Maintaining technical coordination is only part of the task. The systems engineering team must also ensure that the impacts of proposed design changes on other systems or mission elements are fully understood. This includes cost and schedule effects in addition to technical impacts. Many projects benefit from tracking system changes in a change database. The database may include an evaluation of the impact of each change on critical system technical and programmatic resources. A very effective system can be implemented that establishes only whether the resource consumption increases, decreases, or stays the same. More complex systems may quantify the impact to each category or provide levels of increasing or decreasing use of a resource. The database can then be used to seek patterns in the system changes. Additional systems engineering resources may be directed toward systems undergoing a disproportionate amount of change or toward systems generating significant increases in resource requirements. Detailed change tracking data is particularly valuable for planning future projects. The change-tracking database can be easily implemented in any standard spreadsheet or database tool such as Excel or Access.

A configuration management plan typically identifies how the design will be controlled over the course of development and operations. For example, the plan should identify

when each design element will enter each level of configuration management. The document also addresses the details of configuration management pertaining to document control, material control, configuration control, software configuration management, and so on, but it is expected that the configuration management plan will largely reference standard procedures for these activities.

Technical Performance Metrics (TPMs): The systems engineering team is responsible for establishing project-specific system-level technical performance metrics and design guidelines that will be applied across the project. The mission system engineering team is also responsible for working with the segment system engineering teams to ensure that these metrics are margined and tracked. Table 10.5 highlights some of the typical system level TPMs.

Requirements Verification: A critical element of systems engineering is ensuring that every requirement is verified. Therefore, the systems engineering team must develop a thorough compliance matrix that identifies the verification method for each requirement. At a minimum, this matrix must include all requirements in the system-, segment-, and subsystem-level requirements documents and specifications. Since verification must be performed and documented for every requirement, the compliance matrix is often managed as part of the requirements document. A verification method must be specified for every requirement at each level of the requirements tree hierarchy. The verification must be performed by at least one of the standard four methods: test, demonstration, analysis, or inspection. In addition to indicating the verification method, the compliance matrix should provide traceability to the test procedures or analysis used to verify the requirement.

System Testing: Once each requirement is assigned a verification method, the systems engineering team can begin developing the test plans. For a mission, segment test plans are described in the system test plan. This plan describes how tests are used to verify that each of the mission segments successfully work together. Together with the subsystem lead engineers and the integration and test engineers, the segment system or lead engineers are responsible for developing test plans for their segments. The mission systems engineering team is responsible for reviewing each plan and ensuring that it adequately tests the segment and its interfaces to other segments. Test plans are required for the spacecraft, payload, and ground systems. Mission operations and payload operations test plans may be appropriate for those segments as well and should be called out in the SEMP if appropriate.

TABLE 10.5

Common System Level Technical Performance Metrics (TPMs)

Mass-Related	Other	CONOPS Dependent	Software	Integration and Test/Mission Ops
Dry mass margin	Jitter performance	Battery DoD	CPU utilization	Limited life usage
Integrated mass	System pointing	Propellant usage	Volatile memory utilization	Component run time
Mass uncertainty	Time	RF link (up/down) performance	Non-volatile memory utilization	System run time (mode dependent)
Center of mass	Data bus	Navigation		NVR deposition
Balance mass predicts	Power margin	Thermal predicts		Particulate contamination
	Delta-V (deter. and non-deter.)			General trend data

The completed test plans are used to develop the detailed test procedures that fully test the segment and mission functions. Typically, many members of the project team develop and execute procedures. The MSE and the segment lead systems engineers oversee and provide support to this effort. The mission and segment system engineers shall ensure review of all the test procedures and are accountable for the completeness and quality of the system and segment test procedures.

During the testing process, the segment system engineers or segment lead engineers aid the test team by reviewing completed test procedures and investigating anomalous results. If an anomalous result leads to a design change, the segment system or lead engineer is responsible for ensuring the technical integrity of the solution. In particular, the mission and segment system or lead engineer shall evaluate the change and verify that it does not create unwanted effects elsewhere in the system.

Systems Engineering through the Project Life Cycle

While the bulk of systems engineering activities have been described at a high level already in this chapter, these various responsibilities differ in importance depending on the specific life cycle phase being executed. Some skills, such as technical management and effective communication, remain critically important regardless of phase and are essential throughout the project's execution.

The life cycle process described in the following text tends to be NASA-focused. It should be noted that non-NASA projects, especially those that fall under the DoD acquisition process, do require a similar flow with different names and focus on operational acquisition and sustainment. Reference DoD Instruction 5000.02 for details and Figure 10.11 noting the

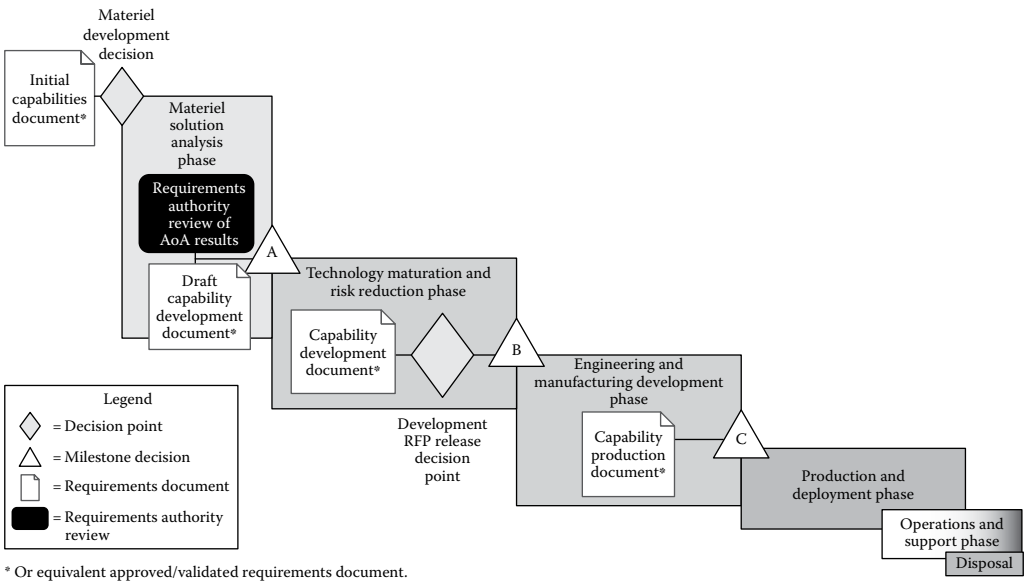


FIGURE 10.11
Overview of the DoD capability requirements and acquisition processes. (Data from Department of Defense Instruction 5000.02, January 7, 2015.)

material solution analysis; technology development decision; engineering development; and manufacturing, deployment, and operational phases.

Concept Formulation: The purpose of this phase, often continually performed by concept study groups, is to devise feasible concepts from which new projects can be selected. The emphasis is on establishing the feasibility and desirability of potential concepts. Analyses and designs are accordingly limited in both depth and number of options. Concept formulation, within the NASA community, typically occurs from the time a mission concept is originally conceived through its initial concept study and/or proposal. This same period occurs in the defense community from the time a specific system need is identified to the time a contract award is issued. During formulation, the top-level (i.e., mission, or often in NASA's case, science) requirements are established and the system architecting takes place. Fundamentally, the mission level requirements are defined by either the science objectives to be achieved or by the specific operational needs or capabilities looking to be fielded.

Many organizations utilize some type of concurrent engineering activity to develop an initial proof of concept, or point design, used to establish credibility with the sponsor of the proposed solution and to bound the design within the available resources. Some of the common concurrent engineering centers include the Jet Propulsion Laboratory's (JPL) Team-X, Aerospace Corp's Concept Design Center (CDC), the Johns Hopkins University Applied Physics Laboratory's (APL) Concurrent Engineering (ACE) Lab, and Goddard Space Flight Center's Integrated Mission Design Center (IMDC). Each of these centers utilizes a varying range of staff expertise, tools, and historical data to rapidly and efficiently work from an initial set of requirements and constraints to produce a technically closed mission concept, or system architecture. A representative product from a concurrent engineering study is a report detailing the conceptual mission design, flight segment description to the subsystem level, notional payload analogs, required ground segment elements or interfaces, a strawman concept of operations, and a high-level cost estimate of the project. Often, future trades and analyses, risks, and next steps are also identified. Figure 10.12 shows the typical activities and products from APL's concept evaluation process.

Once a selected point solution has been identified, it typically goes on to become the basis for a study or proposal to the government, an outside organization, or other sponsor. Sometimes the external stakeholders can be part of the initial systems architecting or concept development process, although this is not the case for a competitive opportunity where numerous organizations are competing for a single opportunity to be funded as a future mission. The level of technical definition and detail released as a proposal depends on the specific sponsor, and the requirements of the announcement of opportunity, request for proposal, or other governing contractual documents.

During formulation, systems engineering is also heavily involved with the development of the project schedule and cost estimate. The MSE, SSE, and segment and subsystem leads provide the knowledge and expertise to generate the inputs to the mission planner or scheduler. The initial mission schedule is often based upon past performance and engineering judgment used to identify the required tasks to be performed, and how long each task should take to complete. Similarly, early project cost estimates also require engagement with systems engineering. Many organizations commonly use parametric cost estimating tools during this phase, and systems engineering often provides the technical context and inputs used to evaluate complexity, make heritage comparisons, and support cost risk assessments.

Phase A: Project Definition and Risk Reduction: Phase A activities focus on developing a baseline mission concept, detailing technical risks, and maturing any needed technologies. The major focus of this phase is to reduce the risks associated with implementing the

Activity	Intermediate products
Scope problem (typically part of the ACE run)	Potential science and engineering drivers, payload concept, observations, trajectory design
Conceptual design initialization	Initial requirement set, science operations and missions operations, notional payload definition
Requirements refinement and tracing	Traceable set of requirements that are sufficient for concept development
Definition of key performance parameters (e.g., mass, power, data rates, delta-V, etc.)	Key performance parameters and margin requirements/definition
Develop costing model input	Mass, power, heritage assessment, process inputs, etc.
Define technology and risk	Technology maturation plans and risk mitigation
Further concept development/refinement	Conceptual design
Deliver data and support external costing effort	
Prepare final report	Final report

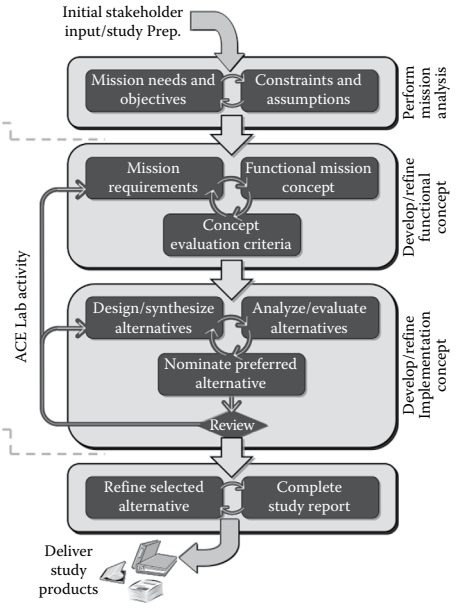


FIGURE 10.12
Overview of the Johns Hopkins University Applied Physics Lab's concurrent engineering concept development process. (Courtesy of JHUAPL, Laurel, MD.)

specific mission concept, and the emphasis shifts to producing an optimal design within the available resources and constraints. This work, along with interactions with stakeholders, helps solidify a mission concept and the top-level requirements on the project.

The systems engineering team focuses on analyzing mission requirements and establishing a firm mission architecture. Activities become more formal and produce more technical depth by considering numerous alternatives. Key trade studies to shape the system architecture and reduce risks, along with hands-on technology evaluations, make up the majority of undertakings during this phase. Goals and objectives are solidified, and the project better defines the system requirements, top-level system architecture, and ConOps. The systems engineering team focuses on the functional allocations to segments, subsystems, and specific components (hardware, software, or staff). Concept studies and reports are developed and present greater engineering detail than in advanced concept studies.

Major trade studies inform system design choices, as a functional baseline for the system and its major end items is produced. The effort also produces various engineering and management documents to prepare for managing the project's downstream processes, such as verification and operations, and for implementing any required specialty programs such as radiation control or planetary protection. This phase also provides the mission schedule to a greater level of resolution and generates bottoms-up cost estimates to support full cost accounting for the next mission phase (i.e., Phase B).

Phase B: Preliminary Design and Technology Completion: During Phase B, a formal project baseline is established, including a flow down of mission level requirements to a complete set of system and subsystem design specifications for the flight, payload, and ground segments, as well as the corresponding preliminary designs. The technical requirements should be sufficiently detailed to establish firm schedule and cost estimates for the project.

The Phase B baseline consists of numerous documents, specifications, and plans that address both the technical and business aspects of the mission. The technical portion minimally includes mission, segment, and subsystem requirements and specifications, ConOps, designs, and verification and operation plans. The business baseline needs to minimally address schedules, cost projections, and project and risk plans. Establishment of a baseline implies the implementation of configuration management processes.

Per the *NASA Systems Engineering Handbook* (NASA/SP-2007-6105 Rev 1), in Phase B, "the effort shifts to establishing a functionally complete preliminary design solution (i.e., a functional baseline) that meets mission goals and objectives. Trade studies continue. Interfaces among the major end items are defined. Engineering test items may be developed and used to derive data for further design work, and project risks are reduced by successful technology developments and demonstrations. Phase B culminates in a series of preliminary design reviews (PDRs), containing the system-level PDR and PDRs for lower level end items as appropriate. The PDRs reflect the successive refinement of requirements into designs."

Additionally, by the mission PDR all required technologies for mission success must be verified to be technology readiness level (TRL) 6 or higher. TRL-6 is typically defined as system/subsystem model or prototype demonstration in a relevant environment (ground or space). This requirement holds in both the NASA and DoD communities; DoDI 5000.02 requires a formal, independent technology readiness assessment (TRA) to be completed by Milestone B (reference Figure 10.12), demonstrating technology performance in a relevant environment. Even if some projects may relax this requirement, especially those specifically looking to employ new technologies into potential operational capabilities, it is strongly encouraged to utilize the Phase A and Phase B periods to mature new technologies, and thereby reduce overall mission risk.

Phase C: Final Design and Fabrication: During Phase C, a complete design baseline, both functional and physical allocation, is produced. Additionally, the team fabricates hardware and codes software in preparation for system level integration. To build confidence in specific hardware designs, engineering units are built and tested in expected environments, and specialty analyses are incorporated into the design. Detailed interfaces are defined. Any design changes must now be controlled and managed, ensuring the proper design details and configurations are effectively communicated throughout the team. As the design is taken to increasing levels of detail, the corresponding integration and verification activities must be planned accordingly.

Throughout Phase C, technical performance metrics, system and delegated margins, as well as schedule and cost variances are strictly monitored for undesirable trends that may warrant corrective actions or additional resources be applied. These activities focus on preparing for the CDR and the SIR.

Per the *NASA Systems Engineering Handbook* (NASA/SP-2007-6105 Rev 1)[3], Phase C "contains a series of CDRs containing the system-level CDR and CDRs corresponding to the different levels of the system hierarchy. A CDR for each end item should be held prior to the start of fabrication/production for hardware and prior to the start of coding of deliverable software products. Typically, the sequence of CDRs reflects the integration process that will occur in the next phase—that is, from lower level CDRs to the system-level CDR. Projects, however, should tailor the sequencing of the reviews to meet the needs of the project." Phase C typically concludes with a system integration review (SIR), with the subsystem and lower-level items being ready for integration.

Phase D: System Assembly, Integration and Test, Launch: This phase focuses on the assembly, integration and test (I&T), and final verification and validation of the system,

including the flight segment being evaluated and tested in the expected environments (e.g., acoustics, vibration, shock, and thermal-vacuum tests). This phase also includes testing and verification of the ground segment and operational elements, performed via comprehensive performance tests (CPTs) and operational simulations. These tests can be performed both with and without the actual flight system and often include ground network compatibility interface testing. Operational simulations also serve to train operations personnel.

Upon completion of local system I&T and a pre-ship review (PSR), the flight system and supporting GSE will be transported to the launch site for integration with the launch vehicle. CPTs, incompressible tests, and launch and early operations simulations will be executed while the flight system is at the launch site, along with contingency planning and simulations. Phase D includes an operations readiness review, flight readiness review, a launch readiness review, and the successful launch of the system. Many projects include on-orbit commissioning activities as part of Phase D, during which the spacecraft and all of its subsystems are functionally checked out, and performance is verified post-launch, in flight.

Phase E: Operations: Phase E consists of the day-to-day operations of the mission, including transiting to the desired orbital location and executing the desired science or operational capabilities. This phase requires various degrees of planning and operational support, ranging from large teams continuously communicating with a spacecraft to lights-out operations or hibernation. Systems engineering involvement is commonly reduced in scope, depending on mission complexity, other than when technical expertise is required to resolve any contingencies and anomalies that may arise. This phase actually produces the products or services for which the mission was originally conceived. At the end of the prime mission, projects may apply for a mission extension to continue activities, or endeavor to perform new mission objectives.

Phase F: Closeout: Phase F deals with termination of the mission, executing established decommissioning and disposal plans, if applicable, and analyzing any returned data to produce the final deliverables to the sponsor and community.

Best Practices and Lessons Learned

Drawing upon multiple decades of successful execution of flight missions, including both civil and military space programs, and both Earth-orbiting and deep-space planetary missions, many key best practices have been established. In fact, most organizations capture their individual lessons learned and best practices and codify these into standards, design principles, or gold rules. A few of these related to systems engineering are highlighted in the following text.

As mentioned at the beginning of this chapter, the MSE serves as the PM's primary technical lead and is integral to controlling the three-legged stool, balancing technical capabilities with costs and schedule. In many ways, the MSE should effectively serve as a deputy-PM; the PM is similarly encouraged to comprehend as much of the technical design and SE processes as possible. Both must work together to lead the project, as is exemplified in several critical areas such as sponsor engagement, earned value management, risk management, and resource management (inclusive of technical resources like mass and power, as well as project costs and schedule).

A small, core systems engineering team can be most efficient and cost effective. Experience has shown that it is desirable to have lighter top-level staffing and organization for multiple reasons. This helps to reduce the layers needing to be negotiated to approve products, sign-off documents, and support other process intensive activities. It also helps to have staff at lower levels that directly interact with the work being performed, and allows problems to be handled at the lowest level possible. Decision-making is also streamlined, although there is a burden placed on the individuals at the top to be solid generalists, and to rely upon the experience and expertise of the segment and subsystem leads. Often the MSE focuses on mission-level elements and outward interfaces, while the SSE focuses on the flight system and inward interfaces. Key SE team members should still include the PSE, GSLE, MSSE, MOM, LVLE, and any specialty (i.e., mission specific) system engineers such as fault management lead, reliability lead engineer, radiation engineer, etc. Note that systems engineering expertise should also be deliberately inserted into target areas unique to each mission being developed, such as areas that have complex interfaces or technical implementations (e.g., exquisite payloads), or major functional areas such as entry, descent, and landing (EDL) scenarios.

Systems engineering is an essential function through the entire mission life cycle. It is also highly beneficial for there to be continuity in the systems engineering leads throughout the mission. Should staffing changes be required, it is desirable to make these at major phase boundaries with overlap between incoming and outgoing technical staff. It is ideal to have the same systems engineering core team present Phases B–D.

The systems engineering leads must assume responsibility as the ultimate technical authority, as they are the individuals that must own the system design, effectively manage the technical tasks of the entire team, control risks, lead reviews, and actively manage AIs and in the end are largely responsible for the technical success for the mission.

Finally, the systems engineering leads need to be strong communicators and serve as the central technical information hub for the entire project. They are the central leaders and team builders, and therefore also require advanced people skills. Often emphasis is placed on technical expertise and capability, but more often than not, it is the soft people skills that separate the great teams and exceptional, successful missions.

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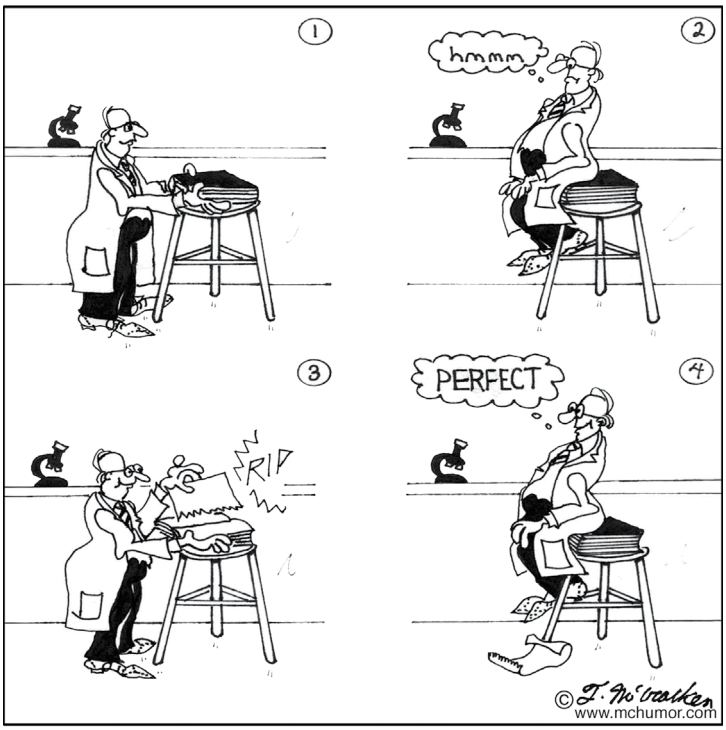
11

Managing Spacecraft Subsystem Development

Karen Kirby and Ann L. Cox

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Getting the specifications just right.

Introduction

Managing the development of spacecraft subsystems is an important aspect of aerospace project management. Space systems are complex entities combining a wide range of engineering disciplines. The decomposition of the spacecraft into subsystems allows for technical management based on functional areas of expertise such as electrical engineering, mechanical engineering, and software engineering. The spacecraft subsystem is generally the lowest managed element in a space system development project; management at the subsystem level varies in magnitude and formality as is warranted by the complexity of the overall system. Subsystem decomposition is also heavily influenced by the organization responsible for the development and delivery of the spacecraft. This chapter describes the common themes of subsystem development.

Flight Vehicle Terminology

A subsystem is a grouping of components and/or functions usually within a common technical engineering discipline. Various subsystems are integrated together, mechanically and electrically, to form a platform capable of hosting the payload to achieve specific

mission objectives. The platform and flight vehicle terminology differs based on the mission objective and destination.

For civilian (e.g., NASA) missions that fly in Earth orbit, the integrated platform is typically called the satellite. After the satellite and payload have completed their individual integration and test, the payload is integrated with the satellite to form the observatory. This reflects the objective to "observe" the Earth or other region of interest with a payload. Depending upon the customer, an observatory's payload may comprise a single or multiple measurement unit(s) to provide radio and broadband telecommunications, weather data, digital imagery, radar tracking, or science measurements to name a few.

Missions that leave the near Earth environment and travel into outer space for purposes of scientific exploration use a spacecraft. NASA and other space agencies sometimes use different terminology depending on the mission's science objective and destination for the investigation; however, the term spacecraft is most often used for the platform to host the science payload. On missions where multiple science instruments form the science payload, the integrated flight systems are commonly known as observatories (such as the Solar Dynamic Observatory). However, at times the flight vehicle is called by the primary instrument's name. Such is the case for the James Webb Space Telescope whose main purpose is to fly a telescope as the primary science payload. The term "flight system" is another name most often used for a deep space exploration whose science payload comprises multiple science instruments (for instance, the Dawn flight system that recently orbited the asteroids Vesta and Ceres).

For national security space missions, equivalent terminology is used, characterizing the platform as the spacecraft or spacecraft bus and the integrated spacecraft and payloads as the space vehicle.

For consistency, this chapter will use the more frequently used terms: spacecraft, payload, and observatory.

Regardless of the payload, the spacecraft may be decomposed into a set of subsystems. The technical disciplines: mechanical, thermal, power, and guidance navigation and control are required for space platforms, and propulsion may or may not be needed to perform the mission. Each of these subsystems must be designed to meet the mission's unique requirements. The result is that it is rare for any two space platforms to have an identical subsystem design. One key difference between commercial spacecraft and scientific spacecraft is that the communication system is the payload in satellites that operate for radio, television, or Internet service providers. For scientific missions, communication is a subsystem used to provide command and status and to return science data to Earth. The payloads for a scientific spacecraft, a commercial spacecraft, or a national security satellite are all generally procured by a separate contract and integrated with the spacecraft platform or bus during system integration and test (I&T).

The subsystem construct is a useful mechanism to break the spacecraft bus into manageable elements. Aerospace companies and government agencies use similar technical disciplines to organize and manage their engineering staff. For this reason, the subsystem is most often implemented by a specific technical organization in the line management structure. This implementing organization includes experts in the subsystem technical discipline, drawing upon other disciplines as needed (e.g., software, packaging). One of these experts will serve as a given subsystem lead and will have overall responsibility of that subsystem management.

Subsystem Overview

The spacecraft consists of the subsystems that support the payload. These subsystems, shown in Figure 11.1, typically include

- *Mechanical or structures subsystem*: The physical structure of the spacecraft, to which all electronic boxes, thrusters, sensors, propellant tanks, and other components and subsystems are mounted. This subsystem must withstand all launch-related structural loads and maintain any required pointing of other subsystems and/or the payload throughout the mission.
- *Thermal control subsystem*: Monitor and control temperatures of all spacecraft components.
  - *Components may include*: Surface finishes, insulation blankets, temperature measurement sensors, thermostatic switches, radiators, heaters, and coolers.
- *Electric power subsystem*: The hardware and software used to generate and distribute electrical power to the spacecraft.
  - *Components may include*: Batteries, battery-charge-control electronics, solar arrays, solar-array controllers, power converters, power switches, electrical harnesses, and other components.

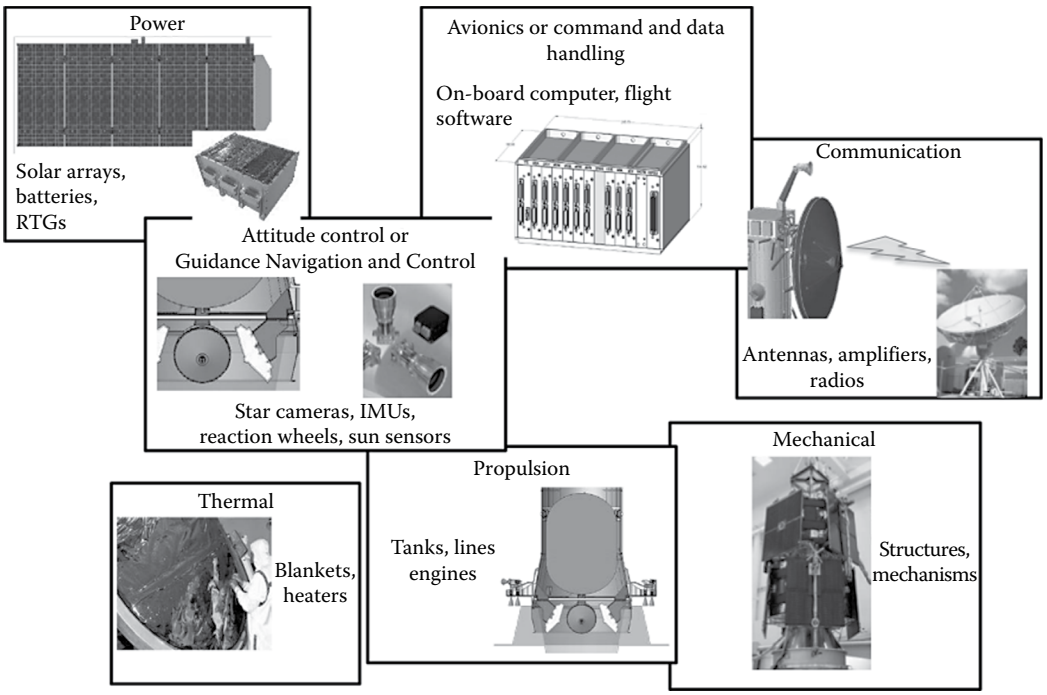


FIGURE 11.1
Spacecraft subsystems.

- *Telecommunication subsystem*: Used to navigate, monitor, and communicate with the spacecraft from Earth and sometimes between spacecraft.
  - *Components may include*: Receivers, transmitters, and antennas.
- *Avionics or command and data handling (C&DH) subsystem*: The hardware and software used to monitor and control the observatory.
  - *Components may include*: Computer(s) and data recorder(s) to monitor and record state-of-health for parameters such as temperature, electrical current, voltage, propellant tank pressure, enable/disable status for various components, and to host command and control, fault protection, and autonomy algorithms.
- *Attitude control subsystem (ACS) or guidance navigation and control (GNC) subsystem*: Used to sense and control the spacecraft attitude and trajectory.
  - *Components may include*: Sun and Earth sensors, star sensors, reaction wheels, inertial measurement units (IMUs), inertial reference units (IRUs), and the electronics required to process signals from the preceding devices and control satellite attitude.
- *Propulsion subsystem*: Thrusters and associated hardware used for changing satellite attitude, velocity, or spin rate.
  - *Components may include*: Thrusters, propellant and pressurant tanks, and associated valves and plumbing.

Subsystem Manager Roles and Responsibilities

Subsystem managers are often also called either control account managers (CAMs) or product development managers (PDMs) to emphasize the significant role they have in managing cost, schedule, and resources to deliver a complete subsystem ready to be integrated with the rest of the spacecraft. The subsystem manager must be a technical expert in their field as well as a leader who is well organized with strong communication skills. He or she is responsible for the concept development and the implementation of the subsystem, often supervising a small team of engineers. This role includes both manager and technical lead as well as being a spokesperson for the capabilities and challenges of the subsystem.

Subsystem managers are accountable to the program manager and lead system engineer for cost, schedule, and technical performance of subsystem development and for verification that subsystem hardware meets subsystem requirements and is correctly integrated into the spacecraft. They have the responsibility for supplying subsystems and components to I&T. In coordination with the system engineers, they determine functional allocation, subsystem requirements and interfaces, and define the subsystem configuration and need dates.

The subsystem managers also have a role on the spacecraft system engineering team to ensure that the system will perform as needed. System engineering is described in detail in Chapter 10. The interaction and roles and responsibilities of the system engineer and

how they flow requirements to the subsystem are addressed there. The subsystem requirements and interfaces are developed jointly with system engineering and are allocated to subsystems from the upper level spacecraft and program requirements. In addition, the subsystem engineer may provide hardware or software constraints in the formulation of subsystem requirements. This is most prevalent with the reuse of existing designs or procured subsystem components.

With project management support, the subsystem manager solicits support from the technical and business operation organizations to provide personnel, facilities, and design heritage to meet project needs. For in-house components or subsystems, the subsystem manager directs the development process, concurs on the design approach, coordinates manufacturing personnel, develops processes or test techniques, oversees the performance of all tests, and supports system level integration and test.

The subsystem engineering team has the responsibility for assuring that equipment is designed, fabricated, and tested to meet all project requirements. This responsibility requires them to generate and control subsystem, component, and procurement specifications, drawings, statements of work, and other related documents necessary to assure timely delivery of subsystem equipment, software, and documentation, which meets the technical requirements and is delivered within the project schedule constraints. The subsystem manager must ensure that the design team implements organization or company compliant design processes; maintains and effectively uses the necessary project plans and procedures; participates in make/buy decisions; and participates in proposal evaluations, negotiations, cost analyses, source selection, subcontractor surveys, and design reviews, as required.

The engineering team is accountable to the flight or mission assurance manager for meeting all reliability, handling, contamination, and safety requirements within their subsystem.

Within the scope of their subsystem, the subsystem managers can be designated by the project manager as the primary interface with the customer and in particular with the customer technical representatives. In these situations, they are authorized to discuss issues, options, and recommendations with the customer; however, they must consult with the project manager before committing to actions outside the scope of the contract.

The primary subsystem activities are shown in Figure 11.2 distributed across typical project development phases, from concept development to operations.

Managing Subsystems in the Matrix Organization

In general, the functional line managers are responsible for supporting the CAMs and for assisting in their progress (both technical and cost/schedule). The CAMs are responsible for staying in contact with the functional managers of the various disciplines involved in their subsystem and for assuring the technical baseline and requesting additional support when necessary.

In addition, the functional managers support the project by:

- Providing qualified personnel to staff the project
- Reviewing and approving cost and schedule commitments
- Monitoring the performance of the staff

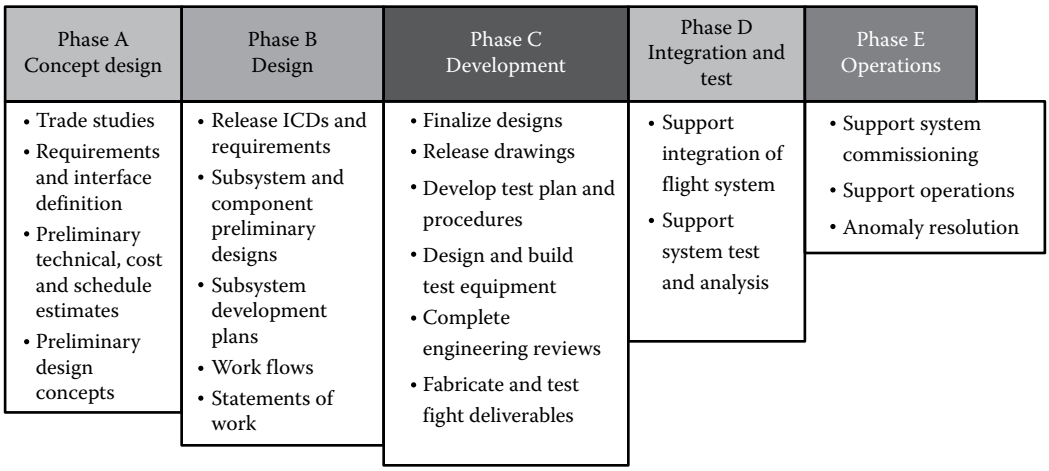


FIGURE 11.2
Subsystem activities by project phase.

- Managing the career development of their staff
- Supporting program-specific needs (specific issues, specialty engineering, surge support, etc.)
- Providing selected services (e.g., manufacturing and environmental test)
- Consulting with and supporting project team members regarding issues, as required
- Leading and/or attending peer reviews and inheritance or heritage reviews
- Ensuring facilities are maintained, equipment is calibrated, and capital investments are allocated to provide the needed technical environment for the CAMs to be successful

Functional line management is often responsible for supporting subsystem deliveries to multiple projects, with each subsystem having its own unique mission-specific variants. Project management is responsible solely for a specific instance of a subsystem that meets the needs of one project. There is often a healthy friction between the line and project in a matrix organization. The goal of line management is to provide efficiency and cost savings by using common products for multiple projects or related applications where possible, balanced with the judicious incorporation of new technology for the advancement of the subsystem as a whole. Projects generally want the minimum cost and technical solution that meets their requirements. Subsystem managers must walk the line between their line management and project management and find the optimal solution that meets the needs of both the organization and the project.

Building Subsystem Teams

Subsystems often include multiple assemblies or elements and each has a designated cognizant or lead engineer responsible for the development and test of a subset of the subsystem. This could include procured items and items built in-house. It is important for these

engineers to collaborate effectively so that their hardware and software elements will work together when they are integrated. The requirements must be sub-allocated to each element and specifications and interface documents written to ensure each will do their part in the larger system. If the subsystem is complex and includes many sub-elements, then a system engineer may be required to help manage the subsystem requirements and interfaces.

Design engineering, analysts, and test engineering disciplines are also included as part of the subsystem team. All of these engineers must work together to accomplish more than any of them could realize individually. Effective technical team leadership is key to keeping everyone working toward a common goal.

Subsystem Development Process

The subsystem development process is depicted in Figure 11.3. It begins with a planning phase. This includes preliminary cost and schedule estimates based on early concepts. These plans are iterated during the requirement development phase. The technical products are developed during the design and implementation phases of the project. Subsystem test and verification are completed prior to delivery of the subsystem to the project for system integration and test.

Planning Subsystem Development

Planning the subsystem development begins with a review of sponsor documents and the statement of work to understand what is needed. It is also important to understand and compare the sponsor requirements with the quality management requirements of the implementing organizations, since there could be requirements driven by internal quality control processes as well as those from the customer. All incoming system requirements are analyzed and distributed to the appropriate subsystems for further decomposition into hardware, software, and analytical requirements for each subsystem. These requirements are evaluated and compared to existing products, heritage designs, and commercially available components in order to select the subsystem architecture. The architecture must be defined in order to define resources and provide cost and schedule estimates to project and line management.

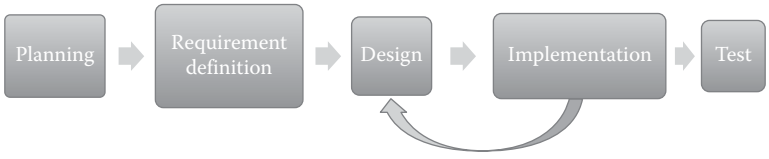


FIGURE 11.3
Subsystem development process.

Technical Product Development

The subsystem development process begins with a flow down of subsystem requirements and interfaces from the spacecraft system to the subsystems. The subsystem manger identifies and conducts trade studies to assist in determining requirement feasibility and implementation options. These may include make/buy decisions as well as technical implementation alternatives, including the use of existing designs and the introduction of new technology. The subsystem is further decomposed into components, which are managed by component level engineers reporting to the subsystem lead engineer. Requirements are sub-allocated to components and between hardware, software, and analytical elements. Component-level specifications are written for items to be procured and the subsystem manager coordinates with the organization's subcontracts office to establish necessary subcontracts. Subsystem managers are responsible for coordination across the project with system engineering, packaging engineering, product or system assurance, ground support equipment (GSE) engineers, and integration and test engineering. Manufacturing and assembly may be done locally in-house if the implementing organization has in-house fabrication facilities, or out-of-house using fabrication service facilities. The subsystem manager is responsible for working with subcontractors, either for services or to procure components and/or delivered units. Managing out-of-house activities requires all appropriate requirements to be flowed to the vendor and includes varying levels of contractor oversight by the subsystem team.

Project quality assurance and mission assurance organizations provide support to the subsystem management and engineers in support of these activities. Adequate funding for these purposes must be taken into account or provided by other areas of the project.

Subsystem Test and Verification

Once the subsystem is built there is significant effort involved in verifying the requirements are met and validating that it meets all the requirements of the spacecraft system. The subsystem test engineers write test plans and procedures, and certify that all test equipment is ready to test the flight hardware. The subsystem test results become part of the end-item data package that is delivered with the flight units. These can be used to compare with test data taken later in spacecraft system test for trending purposes and validation that the design continues to meet all requirements. After subsystem testing, the flight hardware is delivered to the spacecraft system where it is integrated and tested in concert with the rest of the spacecraft subsystems if possible.

Subsystem Change Control

Engineering changes that affect higher-level requirements, external interfaces, cost, or schedule are managed at the system level with a formal engineering change request and review by a change control board and approval process. Subsystem managers ensure

that any changes in their subsystem that affect the project will be brought to the appropriate change control board. Release and revision of subsystem-level documents and drawings require review and approval signatures as defined in the project configuration management (CM) plan and signature authority memo, which may be a separate document or incorporated into the CM plan. Subsystem-level changes that are wholly contained within the scope of the subsystem are managed at the subsystem level. The subsystem manager may choose to hold a subsystem change control board for a complex subsystem with a large subsystem team, or through a less formal process to review and approve changes via email or other electronic routing tools. The level of subsystem change control will vary based on complexity, risk classification, and sponsor requirements.

Subsystem Deliverables

The final product for the subsystem is an integrated, qualified flight subsystem and any required spare components and GSE. Many development units may be necessary to progress a subsystem concept through to delivery of the flight subsystem. The type and quantity of subsystem delivered units will vary based on customer requirements and on the risk classification of the project. Prototype units may be used to checkout new or significantly changed designs early in the conceptual design phase. To provide early design feedback, prototypes generally do not use flight parts and may only represent a subset of the unit (a single circuit card assembly of a box, e.g.). Usually these units are not used after prototype testing is completed although sometimes they may be implemented in engineering model units. After a new or significantly changed design has completed prototype testing and the design revised according to the test results, either a qualification unit and/or an engineering model is fabricated to test the preliminary design. A qualification unit is sufficiently representative of the flight unit (form, fit, function, flight parts, manufacturing, and test processes). These units are tested to higher levels than expected in flight in order to demonstrate design margin and qualify the design. Due to the "over-testing" of qualification units, they are deemed no longer suitable for flight use, but may be used to support ground testing (component, subsystem, system). The flight-like expense and restricted use of qualification units limits their implementation to missions with a higher risk classification. Engineering model units, which are not required to include flight parts and processes, are tested to flight levels although typically for shorter duration (acceptance test). They serve multiple purposes. On projects that include the use of qualification units, engineering model builds proceed qualification units. In lower risk missions, engineering model units are used, rather than qualification units, to demonstrate new or modified designs. Engineering model requirements are established to facilitate delivery to and use in a system testbed after completion of subsystem use.

The number of flight and spare units that are required depends on the number of spacecraft being built as spares may be shared among common designs. A project may require that spare units be fully built and tested and available sitting on a shelf ready to use, or they may require spares be delivered as kits of parts and boards to be built up if needed. This later approach has become more common. It provides more flexibility in the event design changes are required to solve technical challenges found later at the system level.

In addition to hardware and/or software deliverables, required subsystem deliverables include documentation such as specifications, models, analyses, block diagrams, drawings, test plans, component test data, and procedures. An end-item-data package is provided with the flight deliverable units, which includes all deliverable documentation. The subsystem engineers must make determinations about the test equipment, simulators, and ground support equipment they will need to support assembly, integration, and test through spacecraft system testing. All of this must be planned early in the project to be included in the subsystem planned lifecycle cost and schedule.

Review Process

A key element of a successful subsystem development process is a thorough and rigorous review process. This includes a formal review process with review boards and action items as well as the less formal peer reviews and engineering design reviews. Sponsors often impose unique requirements or standards that specify the review process. NASA programs follow NASA Procedural Requirements NPR 7120. The Department of Defense, the Missile Defense Agency, and the Intelligence Community have equivalent requirements for their acquisition programs. The formal reviews occur as the project proceeds through its various phases. The preliminary design review (PDR) is the first major detailed design review and it is normally held before formal design drawings are prepared. This is the most intensive review and includes a deep dive into the design because it is often the last chance to make significant modifications to the design without major impacts. Once the preliminary designs are approved at PDR, the subsystem development begins in earnest. It is between the PDR and critical design review (CDR) that the subsystem component requirements and detailed designs undergo rigorous engineering design reviews. These reviews are just as critical to success as the formal sponsor reviews. The engineering review or peer review will bring external independent reviewers together to advise the design engineers and to offer constructive feedback without the overhead of a formal review package. Peer reviews are intended to be tabletop reviews that delve into drawings, schematics, and analysis. Special topic areas such as environments, package, or special fabrication techniques may warrant unique project peer reviews. CDR occurs near the end of the design phase just prior to the design freeze. After the CDR is complete, the fabrication of flight hardware is initiated. A pre-environmental review (PER) is often required before the start of formal environmental testing. The purpose of the PER is to evaluate the preparedness of the test flow, GSE, and facilities and also to ensure that a proper baseline of performance has been established for the test article and that it is ready to demonstrate system performance over environments.

Subsystem Reporting: Keeping the Project Informed

It is important to keep the lines of communication open during subsystem development so that the project is aware of any problems or issues that arise and to minimize the occurrence of inconsistencies such as functional or interface mismatches among

subsystems. Technical, cost, and schedule risks must be factored into the project risk management to evaluate whether they affect the overall project cost and schedule. Subsystem management includes providing routine technical status reports as well as cost and schedule accounting, usually on a monthly basis. Many projects require schedule management, which will require inputs from the subsystem team in order to track progress against the master schedule. Typical projects hold monthly management reviews. These include technical and budget status reports from each subsystem manager. Subsystem engineers are involved in all aspects of the project and are often called upon to present to system engineering teams and to project or line managers. Depending on the classification of the project, there can be significant reporting involved with managing a subsystem.

Subsystem Cost and Schedule

The subsystem manager provides cost and schedule estimates based on the project requirements and assumptions and technical requirements. The cost and schedule will be iterated with increasing detail throughout the project lifecycle. The subsystem manager is responsible for staffing plans, development schedule, and cost inputs. They must be able to provide cost inputs based on parametric models and bottoms-up estimates, both of which may use engineering judgment and vendor quotes depending on the project needs at various phases of the project.

Recently, most government projects have imposed the use of earned value management (EVM). EVM is a technique that integrates schedule and cost to provide an objective basis to measure progress and performance. A project's work is broken down by the work breakdown structure (WBS) into control accounts. Thus, many organizations have replaced the term "subsystem manager" with "control account manager" or CAM. CAMs develop their baseline plan by generating time-phased budgets to accomplish tasks required to produce their project deliverables. Once the baseline plan is established, the CAM reports progress using established EVM methods for each of his/her control accounts. Monthly EVM data analysis helps CAMs consider their past performance and their future performance to complete the work within the approved plan. Schedule and cost variances are assessed to help identify the root cause of a deviation from the plan, determine the impact of the variance on future work effort, and identify corrective actions. The use of the EVM data analysis helps managers consider their past performance, based on the "earned value," and this is used by the project to determine the "estimate to complete" (ETC) value, that is, the estimated cost it would take from the time the ETC is calculated to the end of the planned, baseline work defined for that element in the WBS. This is illustrated in Figure 11.4. This monthly status of cost and schedule performance along with a forward-look at the estimated cost and schedule at completion provides early identification of potential cost overruns and/or schedule delays. This provides the opportunity to implement corrective actions to recover prior to task completion.

Managing Subsystem Risks

Continuous risk management (CRM) is a systematic decision-making process that assesses (identify, analyze), plans, and monitors (track, control) risk elements to effectively reduce or remove possible impediments to the baseline project plan. CRM is therefore executed to

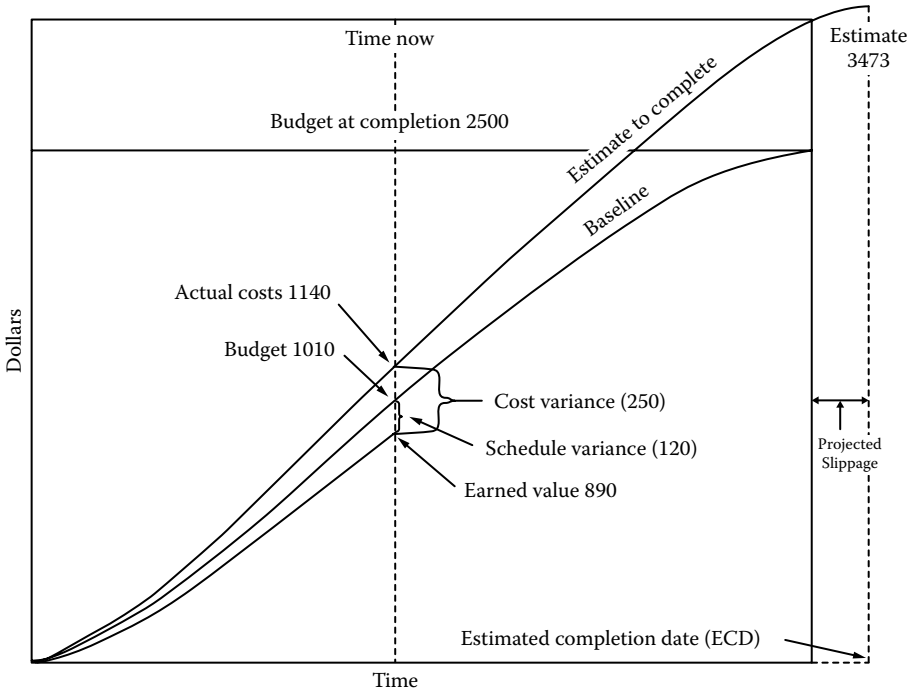


FIGURE 11.4
Standard earned value S-curve.

increase the likelihood that the project goals will be achieved. It provides a disciplined environment for proactive decision making to continually assess all aspects of the program for potential undesired events (risks), determine risk priorities, implement strategies to deal with them, and monitor the effectiveness of the implemented strategies and reassess if necessary.

Keys to Success

It is imperative that the subsystem team work closely with the project and system engineering team to ensure that the subsystem requirements are well understood and that they support the overall needs of the mission. If the system architecture is not clearly defined prior to subsystem design, it is likely to cause changes to the design and associated impacts to cost and schedule.

Likewise, the design should include appropriate margins for growth. These include technical margins (e.g., functional and performance) as well as cost and schedule margins. The exceptional subsystem manager is one who provides flexibility and has the ability to anticipate and accommodate reasonable enhancements without significant impact.

TABLE 11.1

Some Specific Communication Recommendations

Requirements and specifications need to be clear, concise, and verifiable.
Establish common set of units and always label values with units.
Avoid incomplete lists (ending in "etc."), vague words such as "to the maximum extent possible," and passive voice, such as "the datalogger is set" (by whom? when?).
Avoid lumped requirements, should the requirement be split into multiple statements to support traceability and verification.
Consider how the requirement could be misinterpreted or misconstrued.
Rationale for each derived requirement should be part of the requirements database.
Requirements that are unnecessary or over-constrained will drive your costs up.
Each requirement should be traced to a verification matrix.
Use TBDs to highlight the need for further definition but resolve them in a timely manner.
When a lower level implementation affects a higher level, not only trace-up but also back down through other subsystems to determine if other lower levels are impacted.
Interfaces
Establish interface ownership, authority, and decision making for each interface.
Process for interface conflict resolution should be defined and followed for timely resolution.
Document well-defined handover process and procedures.
Change control
Change control process must be followed.
Changes should be communicated to the entire team to ensure all affected S/Ss are cognizant of the change.
Design and analysis
Thoroughly review changes to the configuration, application, interfaces, and environments of heritage designs and analyses to ensure the original design and analysis is well understood and valid.
Not all parameters scale linearly.
Designs that span multiple drawings should be checked end-to-end.
Rework is a fact of life—consider capability to rework during design.
Handling and test procedures need to be evaluated for impact to analyses (such as reduced life).
Design, handling, and installation should minimize likelihood of foreign object debris (FOD) from entering the hardware.
Design should allow for adequate inspection.
Analyst should inspect the actual hardware.
When reusing models and/or analyses, review the assumptions that went into it.
Review of qualification data should confirm that sufficient engineering data exists to base the qualification on.
Check that all space environments were appropriately accounted for in the analysis.
Analysis should account for dimensional tolerances.
Analysis should not be biased. Don't discredit data that doesn't fit your theory w/out sufficient understanding and rationale.
Testing
Test should be for analysis verification, not discovery.
All testing must be preceded by prototyping and/or analysis, followed by model correlation and updating.
Testing should simulate all operating modes and conditions through several cycles.
Test procedures should be adequate to prevent damage to hardware during testing.
Include checkout of test set-up, equipment, and procedures. Where possible, perform a simple test before the full-up test.
Include step to verify polarity of equipment, phasing mistakes is one of the most common sources of test failure (especially ACS).

(*Continued*)

TABLE 11.1 (*Continued*)

Some Specific Communication Recommendations
Test sets should collect all relevant data and enable trending.
Test set should be able to capture transient events.
Test data should be thoroughly reviewed for trends, oddities, "out-of-family" values, and other indicators of potential anomalies.
All test anomalies should be investigated in detail and through the entire failure tree.
Don't mistakenly attribute the failure to GSE or test setup.
Don't stop the investigation once one likely cause is determined, often multiple contributing factors are the cause.

Some challenges will inevitably occur that are outside the control of the subsystem manager. A sampling of these could include vendors not meeting deliveries, overbooked manufacturing facilities, key parts that do not meet specifications when delivered by the vendor, or loss of key personnel. For these types of problems, the subsystem manager will work closely with the project manager and technical management to identify solutions and work-arounds (Table 11.1).

Regardless of the project phase, communication and teamwork is paramount to a successful development project.


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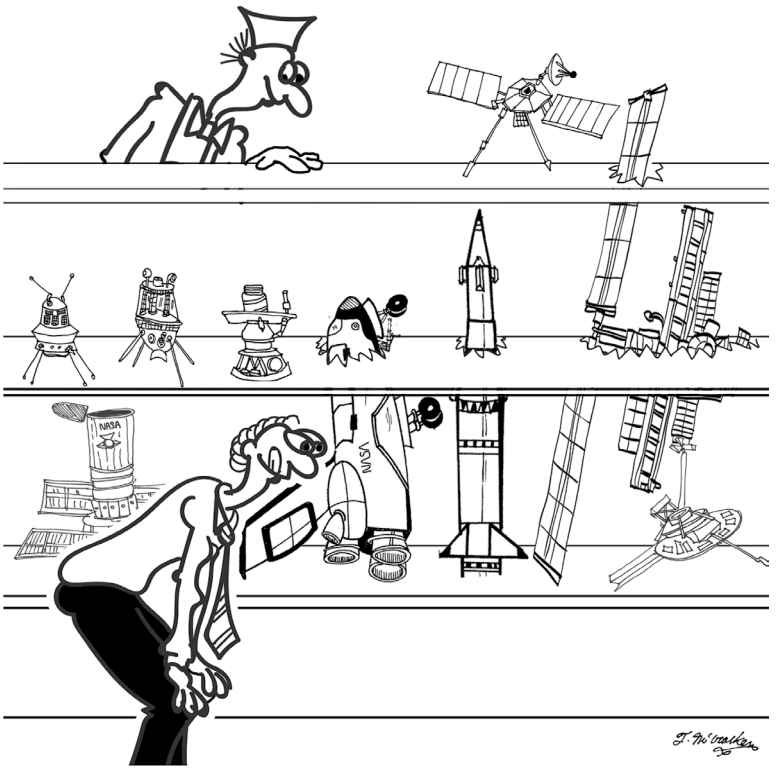
12

Managing Science Instrument Payloads

Kim Cooper

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DESIREMENT VERSUS REQUIREMENTS

Understanding the Science Instrument Procurement Process

Science instrument payloads on space missions may be selected as part of the mission selection process or in a separate solicitation that occurs after the spacecraft or mission is selected. In either scenario, it is important to be able to hit the ground running immediately after the science instrument payload selection. This minimizes the amount of time spent in contract negotiations and maximizes the amount of time for "real" work. A successful start is facilitated by the payload managing institution's advanced preparations for subcontracting to the selected organizations, having an experienced payload management team, and early team building across the payload teams. An experienced payload management team has a full toolbox from which to draw.

Advanced Procurement Preparations by the Payload Managing Institution

The science instrument payload teams are typically comprised of people from many institutions and may involve several layers of subcontracts. Subcontracts tend to take extended time to negotiate and execute since agreement is required on the statement of work, list of deliverables, major milestone schedule, cost, and contractual terms and conditions. Institutions often differ from one another in the content of contractual terms and conditions, and the more layers of subcontracts, the longer it takes to have everyone under contract. To minimize delays in initiating work, it is advantageous for the payload managing institution to have draft versions of the contract elements available for quick release upon selection to start the subcontracting process. Even with carefully advanced preparations, there is typically at least one payload team that is time-consuming to get on contract. In this situation, the payload and subcontracts manager have another procurement tool available—a "letter contract." This defines initial contractual boundaries to enable work to start in parallel with finalizing the overall subcontract.

Building an Experienced Payload Management Team

When the science payload is comprised of teams that span several institutions, it is important to have an experienced payload management team. The payload management team is the interface *voice* between the science instrument development teams, the spacecraft development team, and the mission operations team. Each mission has its unique challenges (mass, power, thermal, electromagnetic interference, uplink/downlink volume limits, launch window schedule constraints, etc.). The payload management team, both technical and programmatic, needs to be able to understand the challenges and bring all the necessary parties together to resolve issues within the constraints of the mission design (Figure 12.1).

By the time the payload teams are on contract, there is a documented, time-phased list of deliverables that support the instrument payload development. Accompanying this list, typically called a subcontract deliverables requirements list (SDRL), is a deliverable items

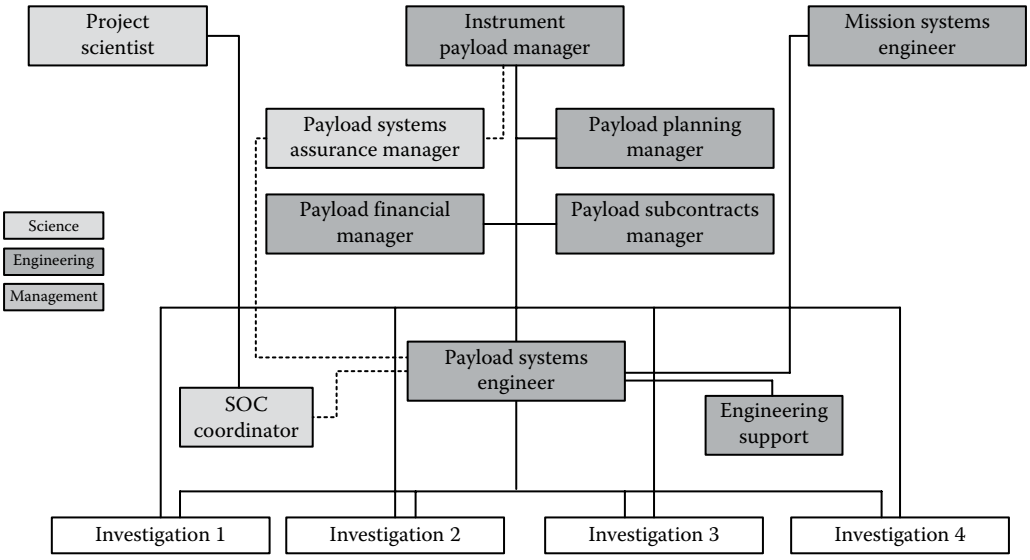


FIGURE 12.1
A sample payload management team organizational structure.

description (DID). These deliverables are due at different cadences throughout the development cycle. They can be due weekly, monthly, tied to major review dates, or linked to significant tests or other relevant mission activities. A tool that has been found useful to both the payload management team and the instrument teams to manage on-time delivery of these various items is a weekly "burn-down list." This list is quite daunting at program initiation due to the sheer number of items, but if crafted in the right way, it can highlight items due in the near term (2 weeks) and items that may be overdue. It is also a useful tool to list special request items that originate from engineering meetings or program level requirement documents that need to be reviewed for feedback to be provided. It is a two-way communication tool—containing actions of the payload team as well as the payload management team. An added positive aspect of the burn-down list is that it is a single place where the payload managers can record and track receipt of numerous deliverables. When managing several instrument teams, without this recording discipline, it can be challenging to recall which teams have delivered items and which are overdue.

Return-on-Investment of Early Team Building

Science payload management teams, similar to any management team, spend a significant amount of time during the life of the project fostering excellent communication and resolving issues promptly. An effective way to set a successful communications baseline is to get all the teams together at one location for a kick-off meeting soon after selection. This is a perfect opportunity for the various teams and the science payload management team to meet. It provides a venue for the payload management team to share its *communication expectations*. This can span frequency/content of regular status reporting to special-topic technical interactions

to major milestone reviews to deliverables to a path to resolve issues as they arise. Another benefit of this team-building meeting is to provide *clearly defined roles* of the members of the payload management team, which goes hand-in-hand with the communication expectations. As with any communication—this gathering is intended to be two-way. The payload management team needs to be ready to listen to the teams as they share potential issues and challenges that they face. This will set a foundation of *trust* across the teams that the payload management team will be the science team's voice back to the spacecraft development team.

In addition to early team building across all of the investigation development teams and the payload management team, equal effort needs to be applied to the relationship between the investigation teams and members of the spacecraft development team. The payload systems engineer is typically the person that brings the spacecraft development team and the investigation teams together. However, it is helpful for the instrument system engineers to have opportunities to communicate directly with the spacecraft systems engineers to ensure that written requirements are being interpreted correctly. The tool that the payload systems engineer uses to facilitate this is to hold weekly engineering meetings, with agendas published in advance, so that the particular system engineers from both the spacecraft and the instrument teams can attend for technical exchange.

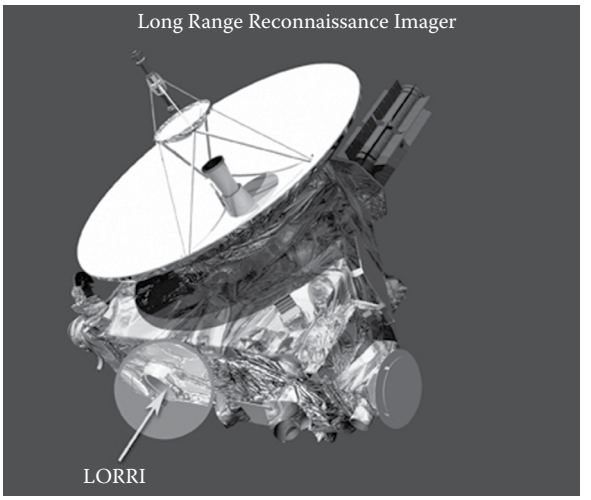
Understanding Science Instrument Development

The science payload teams propose instruments based on a set of requirements contained within the mission solicitation as well as assumptions for any unknowns from the solicitation. When the science payload is offered as part of the mission proposal, it is often the case that the spacecraft-to-instrument interfaces have fewer unknowns. If the science payload is proposed separately, the current interface requirements may differ from the assumptions made at the time of the proposal. Finalizing these interface requirements will be negotiation during the initial phase of the project.

Deliverable products during the initial phase of the program typically include *requirements definition and documentation*. The project produces requirement documents that apply to the science instruments as well as the spacecraft subsystems. The instrument teams should be actively involved in reviewing these requirements and providing feedback (impacts—feasibility, cost, schedule, risk) to the spacecraft team so the project can balance the project risks and resources when setting the requirements.

The project is also responsible for documenting instrument-specific interface requirements. These are typically captured in an *interface control document (ICD)*. The approach to how these ICDs are generated is project specific. An example of an approach is to have a *general* spacecraft-to-instrument ICD, an *instrument-specific* spacecraft-to-instrument ICD, and a *mission operations center to science operations center (MOC)-(SOC)* ICD. The general ICD captures the instrument interfaces to the spacecraft that are similar from instrument to instrument. The instrument-specific ICD documents interfaces that are unique to a specific instrument with the spacecraft (i.e., thermal, harnessing, etc.). The MOC-SOC ICD documents the instrument communication interfaces (both uplink commands and data telemetry downlink) with the mission operations center. Having these interfaces clearly defined allows the spacecraft and instrument teams to develop their systems (Figure 12.2).

Another important document is the program management plan. This is discussed in more detail in Chapter 10. The program management plan will typically have a section



Long Range Reconnaissance Imager (LORRI)
Mass: 8.8 kg (19.4 lb)
Average Power: 5.8 W
Development: Johns Hopkins University Applied Physics Laboratory
Principal Investigator: Andy Cheng, Applied Physics Laboratory
Purpose: Study geology; provide high-resolution approach and highest-resolution encounter images

LORRI, the "eagle eyes" of New Horizons, is a panchromatic high-magnification imager, consisting of a telescope with an 8.2 in. (20.8 cm) aperture that focuses visible light onto a charge-coupled device (CCD). It's essentially a digital camera with a large telephoto telescope—only fortified to operate in the cold, hostile environs near Pluto.

During the encounter, LORRI images were New Horizons' first of the Pluto system, starting about 180 days before closest approach. Pluto and its moons at that time still resembled little more than bright dots, but these system-wide views will help navigators keep the spacecraft on course and help scientists refine their orbit calculations of Pluto and its moons. Approximately 60 days before closest approach—around mid-May 2015—LORRI images surpassed Hubble-quality resolution, providing never-before-seen details each day. At closest approach, LORRI will image select sections of Pluto's sunlit surface at football-field-size resolution, resolving features at about 50 m across.

This range of images give scientists an unprecedented look at the geology on Pluto and its moons—including the number and size of craters on each surface, revealing the history of impacting objects in that distant region. LORRI will also yield important information on the history of Pluto's surface, search for activity such as geysers on that surface, and look for hazes in Pluto's atmosphere. LORRI provides the highest resolution images of any Kuiper Belt Objects New Horizons would fly by in its extended mission.

LORRI has no color filters or moving parts—operators take images by pointing the LORRI side of the spacecraft directly at their target. The instrument's innovative silicon carbide construction keeps its mirrors focused through the extreme temperature dips New Horizons experiences on the way to, through, and past the Pluto system.

FIGURE 12.2
Description of LORRI Instrument on New Horizons Spacecraft. (Courtesy of JHUAPL, New Horizons website, http://pluto.jhuapl.edu/Mission/Spacecraft/Payload.php.)

that addresses instrument development from the perspective of the program. It outlines the responsibilities of the instrument payload manager with respect to *technical approach*, *detailed scheduling*, *cost and staffing*, *subcontracts*, and *procurements*.

The *technical approach* section of the program plan typically contains a top-level description of the mission (launch vehicle, launch window, trajectory highlights, mission duration, etc.). If there are instrument subsystems that require additional development effort

before use in the flight system, these are identified in this plan along with a timeline for completion of the development.

The payload management team is defined along with its roles, responsibilities, and lines of authority. The payload manager works with each instrument team as they develop their *detailed schedule and cost plans*. These plans are integrated into the overall program plans to ensure they are within the program schedule and cost constraints. Cost, schedule, and technical trades are made while taking into account risk impacts of each decision. Once the technical requirements, cost plans, and schedules are determined, they become the baseline against which each instrument payload team is measured. The program management plan describes what metrics will be used to measure performance to these baselines and the payload manager's responsibility in ensuring that the teams meet these performance requirements. Any changes impacting cost, schedule, or technical capabilities require PM concurrence.

The program management plan defines major payload *subcontracts* and *procurements*. The importance of prompt execution of subcontracts to instrument teams is described in the section on the instrument procurement process. Often, space exploration missions are schedule constrained by launch windows and delays in getting instrument teams on contract can shorten their development schedule. The lead investigators, instrument team institutions, reporting paths, and funding paths are also documented in the program management plan.

Payload development follows a progression similar to that of the spacecraft. Depending on the space mission, the payload development may trail the spacecraft development cycle or run in parallel. As described earlier, in either case, it is critical to have well defined and documented interface requirements. The typical development cycle involves an initial conceptual design, a preliminary design, and finally a detailed design. Each of these design phases is reviewed against a set of predefined criteria. The payload management team is responsible for managing this process for the payload. Success criteria for completion of each design phase are set and communicated to the payload team. Documentation development and schedule milestones are defined for each phase, and the payload management team monitors progress toward these milestones with the goal to keep the instrument teams on schedule. In some cases, the payload management team needs to apply additional resources to the instrument teams. The resources can range from additional staffing to approving increases in power or mass budgets. Risk assessments are made to determine which resources are appropriate to be applied.

Instrument development teams are often small teams. In some cases, these small teams are working on concurrent instrument developments. This can significantly strain personnel resources and cause schedule delays—especially if (when) a problem occurs during development. An important toolbox item the payload management team should have available is identified personnel resources to supplement the instrument team. It is best to have individuals/fabrication houses identified from several technical disciplines. Examples include thermal, structural/mechanical, electrical, materials, technicians, board and assembly fabrication, etc. These individuals and facilities can be at the payload management institution or partner institutions or independent contractors. It is especially helpful to have contractual vehicles in place with some of these more critical discipline experts so that if the need arises for assistance, it is available immediately.

Once a detailed design is reviewed and approved, the instrument teams can proceed into the building and testing of the flight instruments. This progression involves *fabrication*, *assembly*, *integration*, *and testing* at the instrument level.

The payload management team monitors progress throughout this process. Since it is common to run into problems at this time, the payload management team, via the subcontract, has already established problem/failure reporting requirements and procedures. This enables more efficient resolution of the issues. Once the instruments are tested at the instrument level, they can proceed to integration with the spacecraft.

Understanding Science Instrument On-Orbit Commissioning Process

Soon after a successful spacecraft launch, there will be a prescribed period, on-orbit commissioning, in which the instruments need to perform and complete their turn-on, aliveness, and check-out tests. The results of these tests will determine if the payload survived the launch and is ready to proceed into the primary science mission.

During the project development cycle, one of the many sets of requirements that need to be defined and documented is the individual instrument commissioning requirements. The commissioning period is typically relatively tight when one considers that it needs to have time to turn-on and checkout spacecraft subsystems, perform deployments, turn-on and checkout instruments, and possibly perform maneuvers. Due to the time constraints during commissioning, it is important for the spacecraft and payload *requirement*s to be clearly defined and distinguished from *desirements* (i.e., capabilities that are nice to have but not essential to mission success).

Once the commissioning requirements are defined, the next step is to develop a commissioning timeline that integrates needs of the spacecraft and all instruments within the available commanding and data downlink time. This timeline is a very detailed, daily (and sometimes hourly) schedule of events. There will be some activities that can be planned at any time during the timeline and others that must occur in a particular sequence. The payload management team facilitates several working meetings with the instrument teams, spacecraft system engineering, and mission operations team to carefully develop this timeline. Contingencies need to be incorporated into the timeline to account for the unplanned loss of contacts for commanding and downlinking. A well-developed and detailed timeline ensures completion of checkouts by the end of the commissioning period.

For space launches, there is usually a *launch window*. It can vary from a couple of days to several days during which specific launch times are possible, some of which may be very limited in duration. The trajectory after launch will vary if the launch is delayed from the nominal plan of launching at the start of the window. Therefore, it is important to develop backup timelines in the event of a launch delay.

For the reasons described, the advanced effort spent in planning the on-orbit commissioning is critical. As with all planning, to ensure successful implementation, it is also critical to test the plans in advance. Therefore, the mission operations team schedules several scenario testing events throughout the development process. Each testing event focuses on specific features of the event. Examples include spacecraft commanding/downlink, instrument commanding/downlink, maneuvers, health and safety monitoring, anomaly scenarios, etc. Thorough testing in advance pays dividends during the mission.

Understanding Science Instrument Testing

A great deal of time is spent at the beginning of project developing requirements. The top-level requirements are what define a mission. Lower level requirements are derived from these and flowed to the instrument teams. The payload management team facilitates the flow down of requirements to the instrument teams. The instrument teams then derive lower-level requirements that apply to the instrument subsystems.

Once the various components/subsystems of the instruments are completed, before it gets integrated with other instrument components/subsystems, the requirements associated with that unit need to be *verified and validated*. An efficient way to track the verification efforts is to have a matrix of requirements and an indication in the matrix as to what level(s) the requirements will be verified. There is a lot of detail involved in verifying requirements, so it is helpful for each of the instrument teams to use a similar format matrix. Although it takes some time upfront, it will save a lot of time later if the payload management team develops the verification matrices for requirements to promote similarity across all of the instrument teams. There are also software products on the market that generate a verification matrix from requirements that are entered into it.

Due to the importance of the requirements verification and validation, the deliverables schedule will require a preliminary version of this document to be delivered. The payload management team reviews the initial version and provides feedback to be implemented in the baseline version, which is due after the critical design is reviewed. The spacecraft engineering team crosschecks the instrument team's requirements verification plans to ensure that all requirements that were flowed to the teams are being verified.

Due to the uniqueness of the science instruments, in some situations, special facilities are necessary to perform verification tests. For example, if a mission is going to be experiencing harsh temperature environments (i.e., either extreme heat or cold or frequent temperature cycles), the "test-as-you-fly" approach may require that the instrument be shipped to another facility or a special chamber be procured at the developing institution. These approaches take both time and money to implement. This type of special circumstance(s) should be covered in the program management plan.

Poor advanced planning for ground support equipment (GSE) and software can wreak havoc on a schedule. There is a tendency to think that GSE is not needed until the test, so it does not receive development priority early enough. This often leads to last-minute procurements and fabrications to secure GSE. Integration and environmental testing will go much smoother if the GSE is planned out and secured in advance.

Understanding Science Instrument Operations

Once the commissioning period is complete, the mission transitions into the operations phase. Science instrument operation planning occurs as part of instrument development. Depending upon the mission, science instrument operations may occur independently or be coordinated across the instrument payload. If observations are to be coordinated, planning is critical. In some cases, it will require communication among multiple instruments within the payload. These interfaces need to be well-defined and documented in interface control drawings (ICD). The payload management team facilitates the development and maintains these ICDs.

The interface between the instrument teams and mission operations center must be defined early in the project. Some projects utilize a *decoupled* approach with the instrument teams. This can be used when each of the instrument teams can be on and operating at the same time—independently from what other instrument teams are doing. The opposite side of the coin is a *coupled* approach when careful planning needs to occur for each day's operations. Missions can vary from one of these extremes to the other.

No matter how complex the operations phase is, it is essential to test, verify, and validate the plan for operations during spacecraft integration and test. Typically, this is done through a series of mission-simulation tests. The purpose of each test is to verify certain aspects of operations. Some mission simulations focus on spacecraft commanding and others focus on instrument commanding.

Understanding the Science Operations Center and Data Analysis Process

Each instrument team in the payload develops a science operations center (SOC). The SOC will be used for instrument checkout during the integration and test (I&T) with the spacecraft. The SOC is also used to provide commands to and receive telemetry from the mission operations center during post-launch operations. The requirements that define this interface are developed in parallel with the development of the instrument and documented in the MOC-to-SOC interface control drawing (ICD). The payload management team works closely with the instrument team SOC and MOC developers as this interface is developed. It is not uncommon to have to make some tradeoffs between the MOC and the SOCs due to instrument or MOC constraints. Just as with other hardware and software trades, cost and schedule impacts and risks are considered when making these trades. Since the MOC needs to interface with all of the SOCs, the payload management team plays an important role in balancing the requests from the SOCs on the development of this interface.

There is a set of support data products that are provided by the MOC. These are used by both the MOC and SOC for status and planning operations. Each instrument team also defines its science data products to be downlinked from the MOC. The instrument teams use these data products to perform post-processing to develop higher-level data products, which are used to meet science requirements. A delivery schedule is developed for each level of the post-processed data product.

In some cases, multiple instruments on a spacecraft coordinate observations to complement the science analysis. The ability to coordinate observations among instruments is defined and tested during development. Operation plans are then developed to accommodate this approach. Payload management is involved in coordinating instrument schedules during development to facilitate testing of the coordinated operations during I&T.

Understanding the Role of the Instrument PI and the Science Team

The roles and responsibilities for a principal investigator (PI) and science team can vary from mission to mission. Some missions are organized with a PI for the mission; whereas, other missions may have a project science team at mission level with individual PIs for

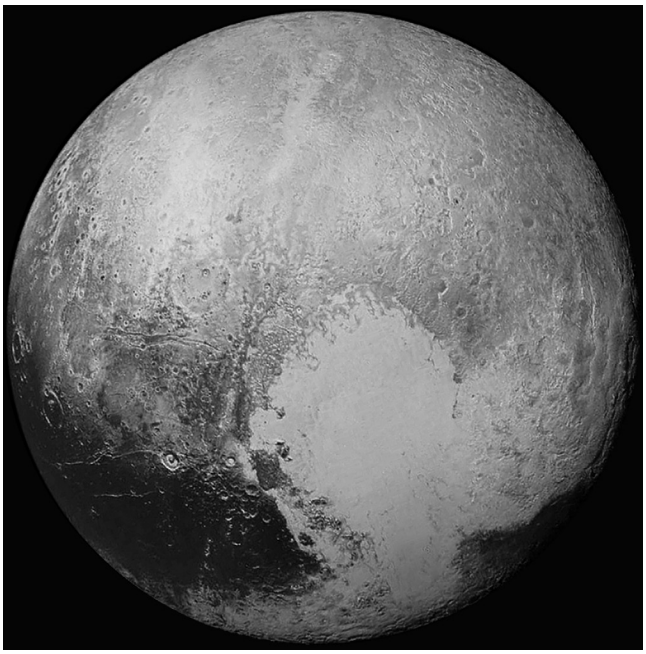


FIGURE 12.3
Image of Pluto taken by the LORRI Instrument on New Horizon. (Courtesy of JHUAPL, http://pluto.jhuapl.edu/Multimedia/Science-Photos/pics/071416-videoStill.png.)

each instrument. In this section on payload management, the scenario of a PI for each instrument will be discussed.

The instrument PI leads the investigation. He/she is responsible for achieving the scientific goals of the investigation. This includes a selection of an experienced team, management of the team, delivery of the instrument suite to the spacecraft, and delivery of the specified data products and scientific results within the negotiated cost and schedule. The PI's team consists of a science team, a management team, and an engineering team to develop and implement the investigation. The PIs and some members of the instrument science team also participate in the project's science working group. This collaborative group ensures that the mission requirements are well defined and achievable within the available resources. As these requirements are parsed to the instrument teams, the payload management team coordinates the contractual flow-down of the requirements to each of the teams. The PIs are ultimately responsible for developing an instrument to be capable of meeting its individual requirements as well as any science requirements that are coordinated across instruments (Figure 12.3).

13

Integration and Test

R. Alan Reiter

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"YOU WERE RIGHT. I HAD A MISPLACED DECIMAL POINT."

Introduction

Integration and Test (I&T) entails planning, personnel, processes, facilities, and other resources required to support the integration and test of the spacecraft (S/C). Although long-range planning must occur early in the program, I&T activities officially begin with the assembled spacecraft bus mechanical structure and continue through S/C launch. Typically, the propulsion system is mechanically installed in the core bus structure before the start of other I&T activities.

I&T is a systematic flow of events, as depicted in Figure 13.1. The first item integrated on the S/C is the harness which is required to provide power and data exchange with all the subsystems on the S/C. The central portion of the harness is installed after it has undergone design, fabrication, and testing, as detailed in the following sections. Other parts of the harness may be delivered on an "as needed" basis while the integration progresses. Before any subsystem integration, the Umbilical Ground Support Equipment (UGSE) rack and cabling are certified for safe connection with the S/C. The UGSE provides power and also enables commands/telemetry with the S/C before the other subsystems are available. Test conductors develop scripts to power the S/C, process and display telemetry, and command S/C components via the UGSE. The first S/C subsystem to be integrated is the Power Distribution Unit (PDU). The PDU is necessary to apply power to other S/C subsystems/instruments, as they are integrated. The second major subsystem to be integrated is the Avionics subsystem, which communicates with most of the subsystems and instruments by providing commands and telemetry. Other subsystems and instruments may be integrated once the PDU and Avionics subsystems are in place. S/C subsystems include many of the following: propulsion, power system electronics, battery, solar arrays, sun sensors, reaction wheels, star cameras, and inertial measurement units. Instruments are of many varieties, including particle

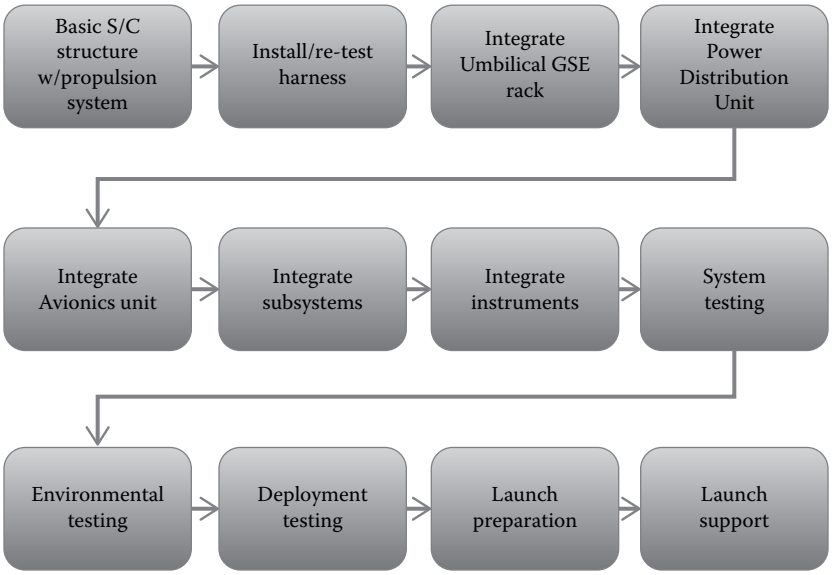


FIGURE 13.1
Simplified integration and test top-level flow diagram.

detectors, radiation detectors, imagers, spectrometers, laser and RF rangefinders, electric field sensors, and magnetic field sensors.

I&T Roles and Responsibilities

I&T involves coordination among a large number of individuals. The core I&T team consists of I&T Leads, Harness Leads, Harness Technicians, Integration Engineers, Integration Technicians, and Test Conductors. It requires additional support from subsystem/instrument leads, systems engineers, mechanical team, guidance and control team, power team, EMC engineers, and many others. A description of the core I&T team includes the following:

I&T Lead(s): The role of the I&T Lead(s) is to plan all activities and schedule facilities to ensure a successful preparation of the S/C for launch. This begins early in the program and continues through launch operations.

Harness Lead(s): The role of the Harness Lead(s) involves designing to the unique requirements of the harness for the mission. This also requires early involvement and continues well into S/C developmental phases during which the system design is finalized and the space vehicle is integrated and tested.

Harness Technicians: Once the harness design is completed, the harness technicians perform the actual harness fabrication and testing while using a full-size S/C mock-up.

Integration Engineers: Integration Engineers are assigned to specific S/C subsystems/instruments to develop integration procedures for the safe integration of the subsystem/instrument to the S/C. Often the Integration Engineers are involved in supporting the subsystem/instrument in their pre-S/C delivery to understand the characteristics of the components to be integrated and to assist with subsystem/instrument level development and environmental testing.

Integration Technicians: The Integration Technicians support the "hands-on" S/C integration activities along with the Integration Engineers.

Test Conductors: Test Conductors develop the scripts required to send commands and display telemetry during all levels of I&T beginning with the UGSE rack through all remaining subsystems/instruments.

I&T Support at Various Mission Phases

The level and type of I&T support vary with the complexity and number of S/C as well as the phase of the mission. Figure 13.2 shows a typical single S/C level of I&T support for various mission phases. It is critical that I&T and Harness Leads have input in early (design) phases of the mission. This involvement ensures that the S/C design details that can drive the cost or complexity of I&T activities are understood before S/C development. I&T Leads focus on testability, which must be followed to verify S/C and instrument requirements. It also allows the long-term facilities requirements to be scoped and reserved, as necessary. As the S/C and subsystem designs develop, it is important to add harness design support. After the mission critical design review, the harness development can

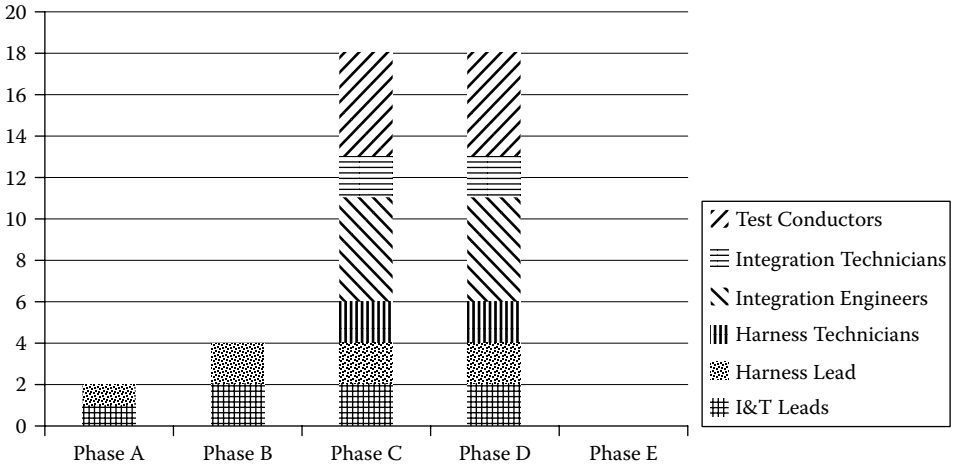


FIGURE 13.2
I&T staff at various mission phases (typical).

begin with the addition of Harness Technicians. Similarly, I&T Integration Engineers and Test Conductors are added to develop the integration procedures and power-up/display scripts used for all subsystems/instruments. Integration Technicians are also required to build cables and support integration activities. I&T support grows during developmental phases and drops off at the beginning of Phase E (operations).

Spacecraft Harnessing

Harness Design: The harness is involved in the early stages of S/C design as well. The harness details are developed from a knowledge of S/C subsystem interfacing as well as the mission environment. Things to be considered in the early phases of S/C development include magnetic, radiation, thermal, and micrometeoroid environments. The harness must also include EMC considerations for self-compatibility. Connectors are often long-lead items that need to be ordered up to 6 months before assembly. Since harness mass is significant to total S/C mass, early design tradeoffs must be considered. Harness routing is also determined and used to analyze the mass balance of the S/C. A full-size high fidelity S/C mock-up is manufactured to support harness development before S/C availability. Harness design is sometimes divided among power, communications, and thermal (temperature sensors and heaters). Power harnesses must be sized to allow adequate current flow for each load without significant voltage drop. This can be accomplished with heavier wire gauge or redundant wires.

Harness Fabrication: Harness fabrication begins about 10 months before integration. It involves manufacturing the harness with tailored lengths to account for routing. The point-to-point wiring is accomplished on the S/C mock-up before any necessary wrapping. The mock-up is also used to determine tie points necessary to support cable mass. After all wiring runs are made, any required wrapping of

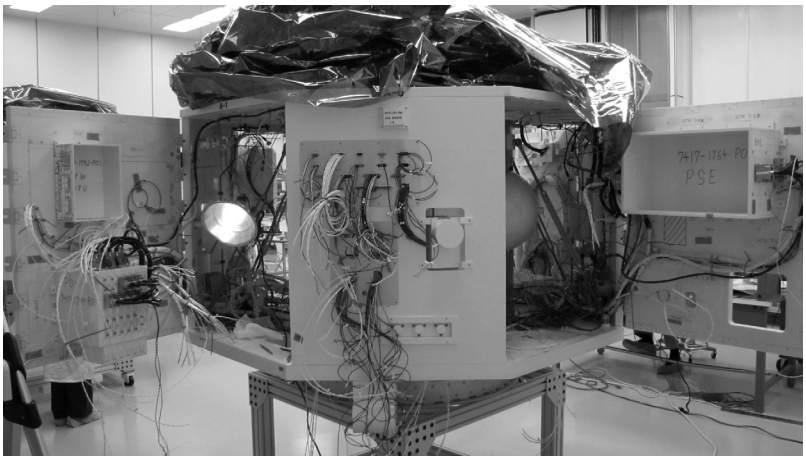


FIGURE 13.3
Harness development on S/C mock-up. (Courtesy of JHUAPL, Laurel, MD.)

the cable bundles is accomplished. External S/C harness is often developed after the internal harness assembly is delivered. The external harness often has additional layers wrapped around the wiring to protect it from the mission environment (Figure 13.3).

Harness Testing: After the completed harness is routed on the mock-up, a Hipot (High Potential) test is performed, which verifies the integrity of the wiring and connectors. It also ensures that signals are routed to the correct end points. After the Hipot testing is completed, the harness is removed from the mock-up and undergoes a thermal vacuum bake-out before S/C installation.

Harness Delivery and Installation: When the tested and baked-out harness is ready to be integrated to the S/C, the Harness Technicians carefully place the assembly into the S/C structure. Following installation, a second Hipot test is performed. The harness is now ready for S/C subsystem integration.

Subsystem Integration

Integration Readiness Review (IRR): All integration activities begin with planning and paperwork. The mechanical and electrical details of every subsystem are carefully reviewed. An Integration Procedure is developed to capture the specifics of the unit to be integrated. Work Orders are developed, reviewed, and signed-off for every activity involving the S/C. The integration sequence is depicted in Figure 13.4. Before integration, an Integration Readiness Review (IRR) is held to review the state of the subsystem. It ensures that the subsystem has undergone all the required testing before S/C delivery. The IRR examines the state of the following items: Integration Procedure, Command and Telemetry Database, Test Scripts, Telemetry Displays, Special Harness Requirements, Special GSE, and Handling Constraints. The status of any liens against the hardware is also recorded.

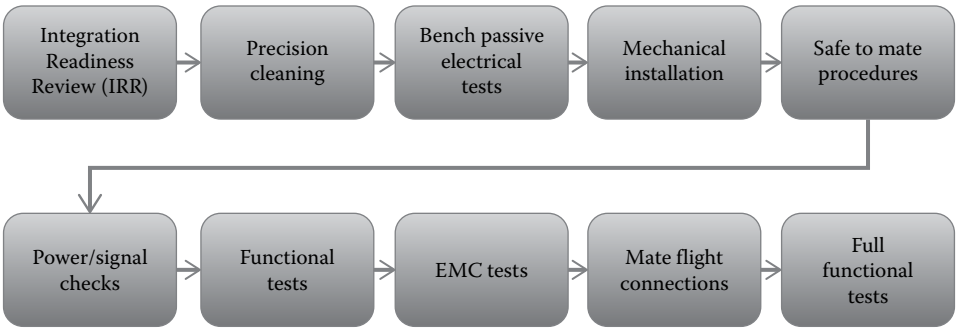


FIGURE 13.4
Simplified subsystem/instrument integration sequence.

Precision Cleaning: Following a successful IRR, the unit undergoes precision cleaning by contamination personnel before entering into the integration cleanroom. The cleaning must recognize any coating constraints for the unit and is designed to meet the cleanliness requirements of the cleanroom and S/C.

Bench Testing: Typically, the unit is visually inspected and undergoes a passive electrical test on the bench. Passive tests verify the unit input/output connections match the schematic and expected S/C interfaces. Measurements are recorded within the Integration Procedure, and any unexpected findings are noted.

Mechanical Installation: At this point, the mechanical team follows a procedure to mechanically move the unit from an electrostatic discharge (ESD) bench to the S/C. The mechanical team attaches the device to the S/C using the appropriate hardware and torque specifications. The mechanical team will also attach ground straps, gasket material, and purge lines, if necessary. Following mechanical attachment, an electrical bonding measurement is performed to ensure correct conductivity to the S/C.

Safe to Mate Procedures: After mechanical installation, a repeat of the passive measurements test is performed on the device. Then, passive measurements are carried out looking into the S/C. When the measurements verify that the correct pins of the device match the expected pins of the S/C harness, powered measurements can be performed. Isolation Break Out Boxes (BOBs), which allow connection and separation on a pin-by-pin basis, are used to safely test connections during powered measurements.

Power/Signal Checks: Isolation BOBs are used to safely connect power, command, and telemetry signals between the subsystem/instrument and the PDU and Avionics subsystems. Connections are made as their signal levels, and polarities are verified. Current In-Rush measurements are performed on the power connections. Current In-Rush measurements ensure the unit does not stress the power system fusing or harness.

Functional Testing: An abbreviated functional test is conducted on the device at this point. The subsystem lead specifies the commands and interprets the telemetry to verify correct operation.

Electromagnetic Compatibility (EMC) testing: Before the BOBs are removed, the electromagnetic environment (EME) engineer performs an EMC test (using the power/ground loop wires) and captures the data using a spectrum analyzer. This test

ensures the radiated and conducted emissions from the unit do not interfere with other S/C subsystems/instruments.

Flight Connections: When the testing is completed, the device is powered down; the BOBs are removed. System Mission Assurance (SMA) inspectors perform a visual inspection of the pins and sockets on both the subsystem and flight harness, followed by the final flight connections. Torque values and torque wrench calibration data are recorded and eventually the connector jackscrews are torque striped. The device is powered ON again, and the EMC engineer performs the final measurements and records them.

Full Functional Tests: The device now undergoes its full functional testing. Full functional tests verify that all testable aspects of the subsystem/instrument are operating correctly. At this point, the device is fully integrated mechanically and electrically with the S/C.

These processes are repeated for each subsystem and instrument until the entire S/C has been integrated.

Instrument Integration

Special Considerations: Instruments must undergo the same considerations of mass, power, and Input/Output requirements that apply to subsystems. Additionally, instruments often have additional considerations such as physical protection of apertures, deployable covers, high voltage, alignment, and purge requirements, as applicable. An instrument Integration Engineer must be familiar with the integration requirements of the instrument and develop an integration procedure with support from the instrument designers. Close coordination is required between the integration engineer and the instrument designers since the instruments are often developed at external organizations and have unique handling and integration constraints. The instruments will also undergo a preship review before the IRR.

Instrument Integration: Instrument integration follows the same process as other subsystems, with the added considerations due to any unique characteristics of the instrument. Extra care must be provided to protect any vulnerable instrument apertures or detectors, and purge considerations must be included to keep internal portions of the instrument clean and dry, as required. Instrument Ground Support Equipment (GSE) designed to stimulate instrument operation must be accounted for during integration and environmental testing.

Performance Testing

Functional Tests: Limited functional testing is used to exercise all essential functions of the subsystem/instrument, such as invoking all modes of operation, loading and dumping memory (if applicable), and responding to input conditions correctly.

Functional tests usually take about an hour to complete depending on the complexity of the subsystem/instrument under test.

Aliveness Tests: Aliveness tests are abbreviated functional tests to indicate the subsystem/instrument is functioning properly, receiving commands, generating telemetry, and supporting its various modes of operation. These tests typically take 5–15 minutes per subsystem/instrument to complete and are used when time is at a premium such as between vibration axes.

Comprehensive Performance Tests (CPTs): CPTs are used to verify all functionality under all conditions. They provide an exhaustive check out of the instrument/subsystem and may take several hours for each to complete. This testing may include writing to and reading from all portions of memory and exercising all permutations of data and operation. The purpose of the CPT is to verify the subsystem/instrument functionality has not changed and that performance requirements are met. A baseline CPT is performed before environmental testing.

Special Testing: Before environmental testing, there are often unique tests required to support subsystem/instrument integration. Specialized testing may include timing tests, phasing tests, alignments, calibration, characterization, and magnetic testing. Additionally, mass properties/spin testing and deployment tests are required for balance measurements and deployment verification, respectively. The unique requirements of the mission, S/C, and instruments determine which special tests are needed (Figure 13.5).

Environmental Testing: Environmental testing begins after the S/C has been functionally verified at ambient conditions. The purpose of environmental testing is to check proper S/C functionality under simulated mission conditions. The preferred "test as you fly" sequence is acoustics → vibration → shock → thermal balance. Thermal cycle tests follow thermal balance tests (Figure 13.6). EMC testing can be performed either before or after the preferred sequence. The exact order of these

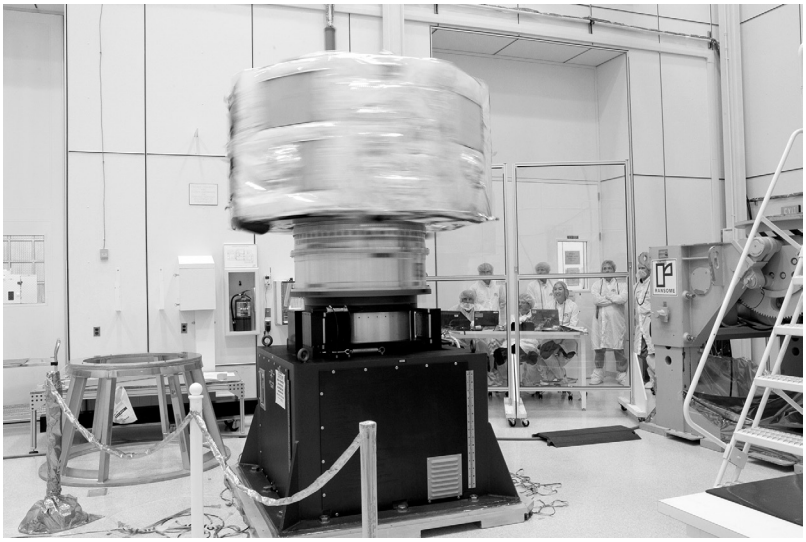


FIGURE 13.5
Mass properties "Spin" testing. (Courtesy of JHUAPL, Laurel, MD.)

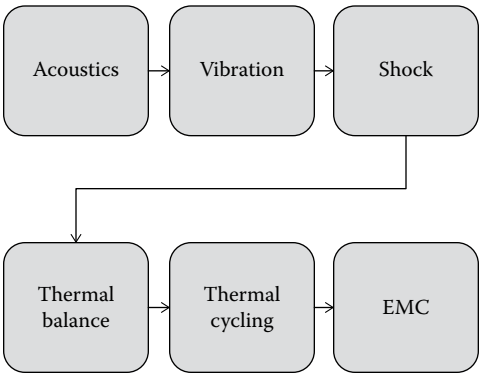


FIGURE 13.6
Typical spacecraft level environmental test flow.

tests may vary depending on facility availability and other considerations. Additionally, a magnetic "swing" test may be required to accurately assess the magnetic properties of the S/C. This test can be used to determine if magnetic compensation or degaussing is needed to achieve the required magnetic performance.

Acoustics: Acoustics testing may be performed before or after vibration and shock testing. These tests involve a different configuration and often a different facility. The configuration allows the application of high levels of sound energy to impinge onto the S/C. The levels and frequencies are designed to emulate the acoustic environment of the actual launch event. Again, the S/C and subsystems are typically powered, but the instruments are mostly unpowered during the acoustics test (Figure 13.7).

Vibration: S/C level vibration testing involves sine survey followed by sine testing in all three axes. The S/C subsystems are typically powered during the actual



FIGURE 13.7
Acoustics testing. (Courtesy of JHUAPL, Laurel, MD.)

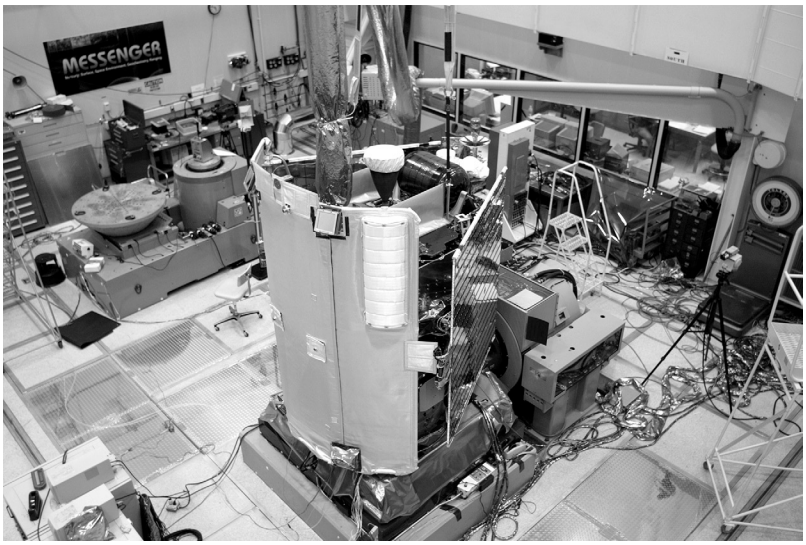


FIGURE 13.8
Vibration testing. (Courtesy of JHUAPL, Laurel, MD.)

vibration testing. S/C telemetry is monitored to ensure correct operation. Instruments are often not powered during vibration because they are not powered during launch and because instruments with high voltage could be damaged during the vibration. An aliveness test of all subsystems/instruments is performed between individual vibration tests to ensure everything is operational. Functional tests are performed before and after vibration testing (Figure 13.8).

Shock: Shock testing is typically performed after vibration testing has concluded. It involves simulating the launch vehicle separation mechanism actuation (e.g., separation events of different launch vehicle stages or firing of the next launch vehicle stage after current stage burnout), which generates a significant shock event. All subsystems and instruments are monitored to ensure the event has not caused any issues with function or performance (Figure 13.9).

Thermal Balance: Thermal Balance testing usually follows all vibration, acoustics, and shock testing. It involves placing the S/C into a Thermal Vacuum (TV) chamber, which emulates the thermal environment of space. The primary reasons for the test are to verify correct operation of the thermal control systems (i.e., thermostats, heaters, heat pipes, and thermoelectric coolers) of the S/C and instruments and to validate the S/C Thermal Model. The temperature is adjusted to simulate the coldest and warmest conditions anticipated for the mission. It often involves localized heaters and coolers to simulate a variety of conditions for the S/C and thermally-isolated instruments. It is also used to exercise cold and hot Power-On conditions for instruments (Figure 13.10).

Thermal Cycling: Thermal cycling tests are performed after the completion of Thermal Balance. The purpose of the Thermal Cycling is to thermally stress all components (subsystems and instruments) to reveal any manufacturing weaknesses such as cold solder joints. Thermal cycles may range from four to six full cycles, typically with plateaus at the hot and cold levels. Since the thermal cycling can last several

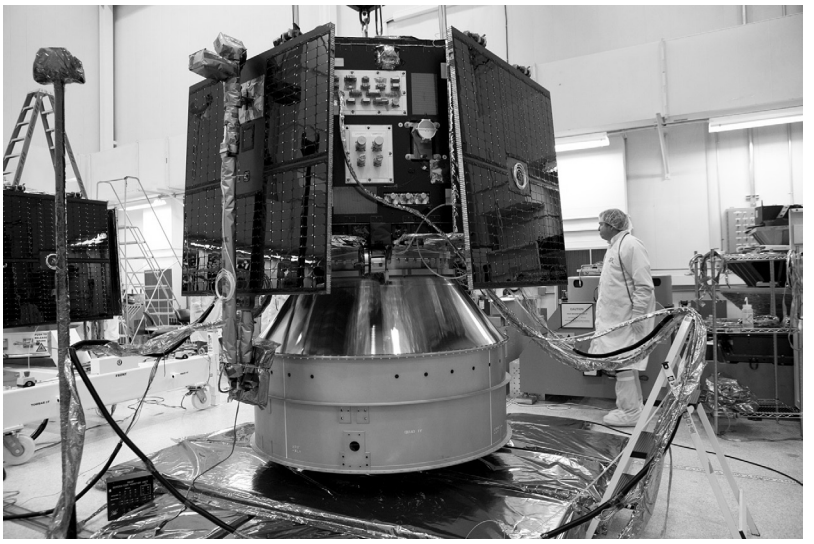


FIGURE 13.9
Separation shock testing. (Courtesy of JHUAPL, Laurel, MD.)



FIGURE 13.10
Thermal vacuum testing. (Courtesy of JHUAPL, Laurel, MD.)

weeks, the S/C often exercises representative mission simulations during the test. CPTs are performed at HOT and COLD plateaus. RF and timekeeping tests are conducted across the entire temperature range.

EMC: EMC tests at the S/C level may be performed before or after the other environment testing is completed. These tests also require a unique configuration and facility. During these tests, the electrical noise level is measured and examined for



FIGURE 13.11
EMC testing. (Courtesy of JHUAPL, Laurel, MD.)

compatibility with all S/C subsystems and instruments, as designed. Self-compatibility is assessed with as many devices powered simultaneously as possible. The testing ensures that electrical noise from all subsystems does not affect sensitive instrument measurements. Usually, a "plugs-out" test is performed where the entire S/C is disconnected from all umbilicals and ground connections. During this test, communication is via the RF system; power is via battery, and major systems are verified operational (Figure 13.11).

Launch Preparations

Deployments: Before launch, it is advisable to perform G-negated deployments (when possible) of booms, solar arrays, and any other deployments including instrument covers. It is important to verify that all actuators are working correctly and that harnessing has adequate stress relief. Full deployment (or simplified "pop and catch") tests are performed early after integration and again at the launch support facility.

Red Tag/Green Tag: Final S/C closeouts including blanketing, removal of Red Tag items, and installation of Green Tag items are performed before mating with the flight adapter.

Fueling Operations: As integration and test nears completion, the S/C and supporting GSE are moved to the Hazardous Processing Facility (HPF). A small team is involved in the process of fueling the S/C.

Final Mass Properties: Final weighing of the S/C and (if required) Spin Balance testing is performed before encapsulation.

Fairing Encapsulation: For many launch vehicles, fairing installation occurs in the HPF soon after the S/C has been fueled. All umbilical cables and purge cables are connected to the upper stage of the S/C. When all connections are inspected, launch vehicle personnel install the fairing. When completed, the fairing is transported to the launch complex. The fairing and upper stage are hoisted and installed on the top of the launch vehicle. GSE and purge connections are made between the launch complex and the S/C.

Final Arming Operations: It is desirable to perform final arming and instrument close-outs before encapsulation. However, sometimes it may be necessary to carry out these operations at the launch facility via fairing access doors. In either case, the final "Arm Plug" installation (to enable deployments and propulsion system) and instrument cover removals must be performed for launch operations to continue.

Facilities Planning

Harness Facility: The harness facility must accommodate the volume and contamination requirements of the mission. A full-size wooden mock-up of each S/C is typically built to allow harness design and fabrication before the actual flight structure. Cleanliness requirements are typically class 100K with smocks and gloves required for handling of the harness.

Integration Facility: The integration facility must be selected based on volume, contamination, lift, and other special considerations such as magnetic cleanliness.

Environmental Test Facilities: Special test facilities are required to support vibration, thermal vacuum, EMC, and other S/C level testing.

Launch Support Facility: The launch support facility is located close to the launch complex. It is typically where the final S/C assembly, test, and fueling activities occur. The S/C and GSE are shipped (by land or air) to the launch support facility. The electrical GSE is reconfigured for S/C testing and must undergo a complete recertification before connection to the S/C. The S/C, which was shipped in a nitrogen purged shipping vessel, must be placed on a work stand for final integration and test. Usually, the S/C final integration begins with the UGSE checkout, as performed at initial integration. Often the flight battery is integrated for the first time. Also, solar arrays and any booms that were removed for shipping are reintegrated with the S/C. The final flight blankets are also installed at the launch support facility. A complete review and sign-off of the interior of the S/C are accomplished by all system leads. If there are any critical alignment verifications with the subsystems/instruments, they are performed. Finally, the protective Red-Tag covers are removed, and most of the flight-configured Green-Tag items are installed.

Hazardous Operations Facility: The S/C is moved to the Hazardous Processing Facility (HPF) for fueling operations and final close-outs. For most launches, the S/C is attached to the upper stage and encapsulated within the fairing. It is now ready for transport to the Launch Facility.

Launch Facilities: The launch facility varies depending on the type of launch vehicle and whether it is a West Coast or East Coast launch (for U.S. launches; noting that new launch facilities are in development in other portions of the country and

the world). In either case, after the fairing is transported to the launch facility, it is hoisted and installed at the top of the launch vehicle. Supporting electrical GSE has been installed to provide power and communications with the S/C. This involves an area to house the electrical GSE and a long length of electrical or fiber optic cables for data exchange with the S/C. Abbreviated functional tests of the S/C subsystems and instruments are performed. Any protective covers are removed from instrument apertures, and a final "Arming Plug" installation is performed, which enables actuation of flight deployment devices and the propulsion system. The S/C is ready for launch. I&T is involved remotely for countdown operations and switches the S/C to battery power in the final minutes before launch. Once the launch vehicle lifts from the launch pad and the umbilical connections are released, the I&T operation officially ends, and Mission Operations takes control of the S/C operations.

Logistics

Transporting Spacecraft: Extra care must be taken whenever the S/C is shipped. Shipment can be merely from one building to another, across town, or across the country. Physical protection, contamination, and magnetic cleanliness must be considered. For moves outside a building, the S/C is placed in its shipping container and transported by fork lift, truck, aircraft, or a combination to reach its destination. The shipping container is designed to protect the S/C from the environment and to provide physical protection. It usually accommodates a clean, purged environment and is equipped with shock protection magnetic sensors to capture the magnetic environment of the transport. Where practical, a magnetic survey of the transportation path is accommodated to assess whether any unusual magnetic conditions exist along the path. The S/C itself is usually bagged to prevent any dust or debris from reaching it. Note that some ranges (e.g., Kodiak Launch Complex) often require ocean surface shipping and so the time in transit in a corrosive environment must be considered.

Transporting Ground Support Equipment: Although less sensitive than the S/C, the electrical GSE racks are also carefully moved with fork lifts for short distances or within air ride trucks for longer distances. The electrical GSE must be recertified whenever it has been transported to a new site.

Lessons Learned

I&T benefits from rigorous applications of Lessons Learned. If possible, a lesson that can be applied immediately and applied to the current program is desirable. Often, the lesson can only be applied to future programs. The I&T team keeps records of Lessons Learned individually and meets at the end of a launch campaign to discuss findings. If lessons are universally agreed, a plan to correct issues for future programs is determined and documented.

Contingency Planning

Inevitably, with complex subsystems and instruments, either the scheduled delivery slips, components are delivered late, or sometimes failures occur requiring rework after a component has been integrated. As mentioned earlier, as long as the PDU and Avionics units have been integrated, the other subsystems/instruments can be integrated independently of any particular order. Integration engineers work diligently to ensure their procedures are ready before planned integration to accommodate delivery order changes. If the PDU or Avionics subsystems are significantly delayed, the use of Engineering Models is evaluated to ensure that other subsystems may proceed, and the delayed Flight units are integrated at a later date. The integration schedule must remain dynamic, able to change integration order based on daily progress as well as unexpected delays during the integration process. In this way, the I&T leads can ensure progress even when confronted with delays or postintegration failures. This flexibility is essential to keeping the overall I&T activities on schedule.

Summary

I&T is arguably the most exciting part of mission development. A successful I&T campaign requires early involvement with S/C design and relies on the timely delivery of S/C subsystems and instruments. I&T leads will apply flexibility to respond to challenges that occur as part of all integration activities. As with all mission phases, however, there are limits to what I&T can do to keep the program on track. It is critical to keep the basic structure, harness, PDU, and Avionics deliveries on schedule. Delays in either of these areas are difficult to react to. If critical subsystems are known to be late, accommodations to incorporate Engineering Models (EMs) can be used to keep the remaining subsystem integration activities on target. With the core components in place, many of the other subsystems can integrate in no specific order. Beyond this flexibility, however, the I&T leads have only extended hours/days combined with schedule program reserves to work with. These last efforts should only be invoked when necessary and only on an "as needed" basis. A successful (and on-time) launch is likely to proceed, following a carefully designed and well-executed I&T campaign.


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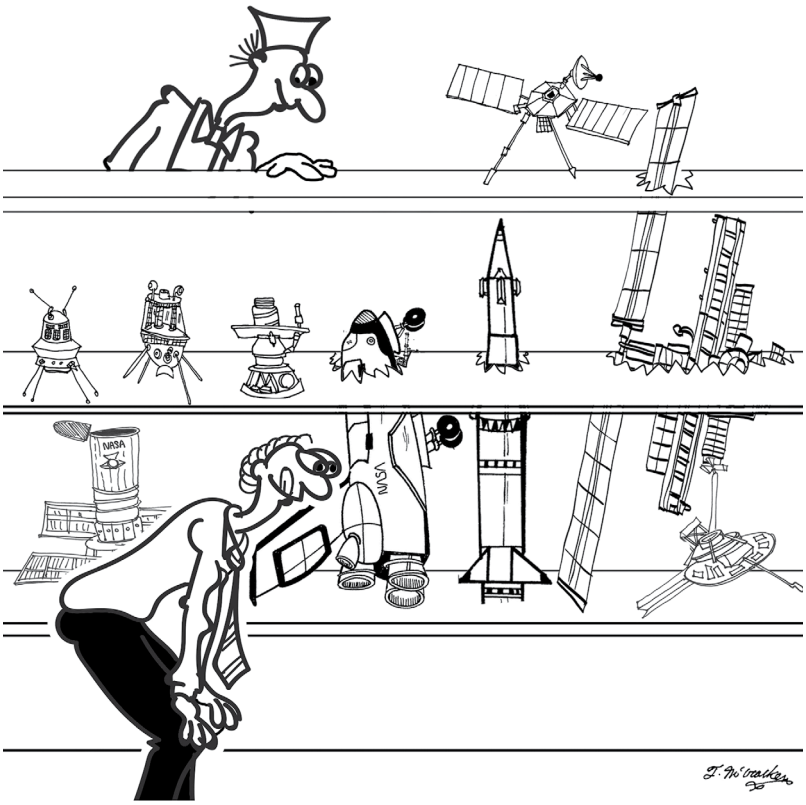
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Managing Mission Operations

Alice Bowman

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DESIREMENT VERSUS REQUIREMENTS

Introduction

The mission operations team is charged with ensuring the space asset design supports the mission operations concept, commissioning the space asset following launch, and conducting postlaunch operations. The best way to ensure fully capable and efficient operations postlaunch is to include a mission operations expert at the very beginning of the proposal stage, preferably the mission operations manager (MOM) and add mission operations team members as the program progresses through the design, build, and operational phases. This assumes an integrated development and operations team, which has proven highly effective in science, research and development, and science and technology missions. For mature commercial missions, often there is a handoff from a development team to an operations team experienced in previous generations of system elements. In the design stage, the mission operations expert evaluates the mission concept and recommends design changes to ensure all postlaunch activities can be accomplished with the as-designed space asset, ground software, and mission operations facility infrastructure. During the build phase, the mission operations experts interface with the space asset and payload engineers to develop the operations prelaunch mission simulation tests to account for all needed postlaunch activities and works with the ground system engineers and

connectivity engineers to ensure a fully capable mission operations center (MOC). This helps to ensure postlaunch mission activities are accomplished in the most efficient and cost-effective way possible. The MOM leads the mission operations team and all postlaunch activities to support operations of the space asset including all payloads. The degree of MOM oversight for the payload teams depends on whether or not the mission is being run as a "coupled" or "decoupled" operation. This is discussed in the "Operations Concept" section. The mission operations team is responsible for developing and maintaining the space asset onboard activities, developing command sets to support these space asset activities, scheduling the ground antennas needed for space asset communication, conducting space asset communications, including but not limited to uplink of commands and downlink of telemetry, maintaining the configuration of the software and hardware simulators to match that of the space asset, and developing telemetry viewing pages. In order to accomplish many of these activities, the mission operations team interfaces with the mission and space asset systems engineers, subsystem engineers, and scientists. Postlaunch anomaly recovery is led by the MOM and the mission systems engineer (MSE).

Mission Operations Responsibilities

The mission operations team is led by the mission operations manager (MOM). The MOM leads the team composed of mission operations analysts and flight controllers. The mission operations team performs the following duties, with specific duties for the MOM highlighted as follows:

1. Develops and maintains the in-flight space asset activities schedule
2. Negotiates and schedules the ground antenna support required for the space asset activities
3. Works with the subsystem and payload engineers to develop the commands necessary to perform calibrations, critical activities, and checkouts
4. Works with the science team or users/command authority to develop commands to perform the desired payload activities ("coupled" mission)
5. Develops a library of reusable command sets to perform a set of actions (i.e., turn on a subsystem, configure for specific space asset mode, and so forth)
6. Works with the mission design, navigation, and guidance and control teams to perform trajectory correction maneuvers
7. Receives and monitors telemetry for any off-nominal trends or alarms
8. Alerts the mission team as per the agreed anomaly notification procedure in the event of an anomaly (MOM)
9. Leads the anomaly recovery board (ARB) along with the mission system engineer (MSE) in the event of an in-flight anomaly requiring immediate attention. For anomalies that do not require immediate in-flight attention, the MSE leads the ARB (MOM)
10. Performs prelaunch mission simulation tests in order to ensure that the space asset can perform its mission postlaunch. These tests are developed to mimic postlaunch activities

11. Maintains the configuration and documentation of the operations software and hardware simulators
12. Tests and verifies all first-time and critical activities using the ground simulators prior to uplink to the space asset
13. Holds team reviews of the commands planned for execution on the space asset
14. Along with the ground system and connectivity teams, prepares and tests the mission operations center (MOC) prior to launch.

There are variations of these duties depending on whether or not the mission is being run as a "coupled" or "decoupled" operation and whether or not the mission is classified or unclassified. This is discussed in more detail in the following sections.

Project Management Support to Mission Operations

In order to ensure smooth, efficient, and effective operations, it is important that the MOM be involved in all program decisions related to operations. This is because implications to operations may not always be obvious, and it is better to err on the side of inclusion. The MOM is an essential member of the program's core team. (The core team is the space asset management team led by the program manager (PM) and is generally composed of the mission system engineer, space asset systems engineer, the mission scientist, and the MOM.) Any requests for mission operations team support need to be first communicated to the MOM. The MOM will determine the most appropriate operations team member(s) to perform the request and prioritize these requests within the many mission operations tasks being performed. It is important that the MOM be involved in program management discussions concerning operations concepts as the MOM can evaluate the proposed operations and many times suggest a more efficient operating concept simplifying and reducing risk to the space asset. The MOM reports to the PM and works closely with the MSE; the mission operations team reports to the MOM; and while the MOM presents to the Principal Investigator (PI) and sponsors, direction and primary interface to the MOM should be in accordance to the reporting structure. If costs need to be cut, it is expected that the PM communicate the target cost so that the MOM can determine the best way to reallocate funds. This is more efficient than just asking the MOM to reduce costs with no guidance. If there are additional requirements, it is expected that the MOM be notified of these new requirements as soon as possible so that the operations concept, test plans, and other related aspects of mission operations can be adjusted to accommodate the change.

Mission Concept and Cost

One of the most important contributions from the mission operations expert during the proposal phase is to evaluate the mission concept and the program risk posture in order to advise the PM, PI, and MSE on the best way to conduct mission operations. Included in this evaluation are advices on ways to reduce costs.

Risk Posture

Mission risk postures range from extremely risk-adverse (Class A for NASA missions) to more risk-tolerant (Class D for NASA missions). This posture factors into the cost of mission operations. Missions that have a very low tolerance for risk necessitate more documentation, prelaunch testing, review, and development of redundant systems either on the ground and/or onboard the space asset. A mission that is more risk-tolerant has proportionately less of this rigor. Mission operations concept development depends on a clear definition from the PM on the risk posture of the mission.

Operations Concept

Mission and space asset complexity also drive mission operations costs. PMs are cautioned that maintaining low-cost mission operations may be difficult for a particular type of mission and/or a highly complex space asset. Additionally, simplifying onboard software many times has the effect of increasing the complexity of mission operations and ground processing. One of the trades that the mission operations expert performs during the concept and design phase is to determine whether or not a mission should be operated as "decoupled" or "coupled," and this is determined mostly by analyzing the mission resource constraints. The recommendation is made to the PM for final disposition. Typically, the mission itself drives whether or not it can be conducted "decoupled" or not.

A "decoupled" operations concept is one in which the payloads are operated independently from the space asset bus and the other payloads. The payload teams are responsible for operating their respective payload. They develop, test, and verify their payload's commands. These commands are delivered to the MOC and placed into that particular payload's uplink queue. During scheduled ground station communication periods (referred to as "tracks" or "passes"), the mission operations team opens the payload queue containing these commands, and the commands are sent to that particular payload onboard the space asset. This type of operation is only possible when the onboard resource constraints are such that the mission operations team does not have to manage common space asset resources. With this operational concept, the mission operations team only commands the power on or off of the payload. All other payload operations are the responsibility of the respective payload team. Examples of the types of missions that lend themselves to "decoupled" operations are those that have constant attitude, adequate power, and sufficient data storage. In these cases, resources do not need to be managed by the mission operations team. Generally, less complex missions have a higher likelihood of being operated under the "decoupled" approach.

For those missions that are directed to be "decoupled," the space asset is designed to provide sufficient payload power for 100% duty cycle operation and gimbaling of the payload platforms. The data recorder is sized to allow sufficient storage space with enough margin to account for some number of missed science data downlinks.

If the mission is constrained in common resource usage (i.e., pointing, power, and so on) requiring management by the mission operations team, a "coupled" operation concept is needed. Missions that tend to be executed as "coupled" are those that are episodic, have limited resources, requiring careful scheduling and management of the different onboard activities so as not to oversubscribe the particular constrained resource. Examples of constrained resources are space assets in which the attitude/pointing directly affects other onboard subsystems causing possible pointing constraints (sun angle constraints, having to point the space asset in order to conduct downlink operations, etc.), and limited power and recorder space (this could be due to a small recorder or excessive usage during a short time period [i.e., flyby]).

"Coupled" operations require more mission operations staff, complete (subsystems and payload) software space asset modeling and simulation, and documentation to account for the management of these resources.

"Decoupled" operations require fewer mission operations staff but more payload operations staff with payload software modeling and simulation resident at the individual payload centers. Subsystem software modeling and simulation are resident at the mission operations facility. For a "decoupled" system, operations responsibilities must be clearly assigned to either mission operations or payload operations. It is suggested that the interface control document capture this division of responsibilities to allow full control of the respective payload without potential conflict or in the worst case, degradation of the mission objectives.

"Decoupled" unclassified operations are normally performed via a rotation schedule where all the mission analysts rotate through the tasks of advance planning, weekly planning, daily planning, and assessment. Additionally, one of the mission operations analyst is assigned to be "on call" to respond to any off-nominal situations. The periods of communication with the space asset are unattended with the exception of critical events, such as launch, trajectory correction maneuvers, and so on. In the event that something is off-nominal with the space asset, the on call mission analyst is notified by an automated message. If the situation requires human intervention, the "on-call" analyst will come into the MOC alerting other team members as warranted.

For classified "decoupled" operations, periods of communication generally have to be attended unless some allowed notification system is approved; classified missions typically have 24/7 staff monitoring system operations.

"Coupled" unclassified and classified operations nominally have the mission analysts (sometimes known as the mission planning team or offline team) performing the offline planning activities and the flight controller team (or real-time team) performing the real-time activities. The mission planning team plans, develops, tests, and verifies the commands to be sent to the space asset and evaluates the results of those commands. The real-time team configures the ground station (mission operations center) and instructs/verifies the antenna complex configuration for space asset communications. "Coupled" unclassified and classified operations normally have most periods of communication with the space asset monitored/attended.

Conduct of Postlaunch Operations

Another factor that the mission operations expert evaluates during the development (proposal, design, and build) phases is implications of who operates the space asset postlaunch. If the asset is to be turned over to the customer for operations following postlaunch checkout/commissioning, there are some added cost and schedule considerations. Documentation must be written with the customer in mind such that all terminology, tests, and operational system description are fully defined and detailed. An extensive training manual is written instructing the customer on all postlaunch duties. It is important that the customer get hands-on training in as many of the prelaunch mission operations activities as possible specifically focusing on those activities that the customer will perform routinely postlaunch. If the vendor is to play any role in postlaunch activities, it needs to be documented and agreed upon. This allows for costing and resource allocation (i.e., retention of prelaunch facilities, documentation, personnel) for postlaunch operations.

Degree of Automation

An important part of determining the postlaunch mission operations cost is evaluating the degree of "smarts" or autonomous capability needed onboard the space asset. Generally,

the "smarter" the space asset, the more costly it is to develop but less so to operate postlaunch. Higher development costs for highly automated systems are also reflected in the need for more extensive ground testing efforts to ensure that the system operates as intended. This leads to a trade between greater automation performed onboard the space asset and more steps to be performed manually by mission operations personnel or by the ground software and then uploaded to the space asset for action. The PM should consider this when determining capabilities/requirements of the flight and ground software.

If a space asset is tasked with quick turnaround requests, the PM should consider incorporating automated ground software that can ingest and perform these activities or parts of these activities rather than relying solely on mission operations personnel to perform all of these operations manually. It is recommended that these types of repeated tasks be considered for automation. This is especially important when postlaunch operations will be turned over to the customer.

Space Asset Communications

The mission concept largely determines the ground antenna system needed for communications. For missions leaving Earth orbit, deep space antenna complexes are needed. The most well-known is the Deep Space Network (DSN) managed for NASA by the Jet Propulsion Laboratory (JPL). Other agencies having ground antennas that can be used are the antenna complexes managed by ESA (European Space Agency), ISRO (Indian Space Research Organization), and JAXA (Japanese Space Agency). For space assets that remain in Earth orbit in addition to those mentioned, there are ground antennas operated by SSC Space U.S. Inc. (formerly Universal Space Network (USN)), SANSA (South African National Space Association), and other individual ground antennas. Once the ground antenna complex(es) are selected, ground software must be developed to provide the interface between the ground antenna complex and the MOC. Additionally, the mission operations team needs to be trained in the ground antenna scheduling process. Missions usually have a signed agreement with the communications provider, and the PM works with the mission operations expert to establish the agreement for antenna communications support.

Proposal and Development Phases

Proposal/Concept Study and Early Development

In the concept and early development phase, mission operations evaluates the mission for ease of operability and makes suggestions on how to increase operability. For example, if the plan is to update software during flight, the ground system software should include this software capability in its suite of software tools. Absence of this ground software tool forces the mission operations analyst to develop this capability using the planning software, which may not be as efficient. Another example is that planned radio frequency (RF) rates might not support anticipated critical activities planned for a certain part of the mission. In this case, the mission operations team works with the RF team to adjust the planned rates so as to better support postlaunch mission activities. The mission

operations team develops mission simulation tests to test the space asset as well as the MOC. These are system-level tests performing known/planned postlaunch activities. Being involved early in the concept and development phase allows this mission simulation testing activity to be planned well in advance. Additionally, mission simulation tests are used to verify system-level requirements. Any required modifications are identified early in the development phase when incorporating changes are less costly than if identified later in development.

Preliminary Mission Operations Concept of Operations

The *Mission Operations Concept of Operations* (ConOps) document is developed by the MSE, generally using heritage as its basis and is written in consultation with the MOM. The ConOps document feeds directly into the *Mission Operations Plan* written by the MOM with the first draft generally due around the mission critical design review (CDR). The *Mission Operations Plan* is a much more detailed document covering operations duties, mission milestones/phases, subsystem and payload operations, command development, mission simulations, and interfaces.

Ground Antenna Costs

Generally, the cost associated with the mission-required ground antenna support is provided by a member of the mission operations team, normally the MOM. The mission concept and risk posture are evaluated along with the various mission milestones and space asset configuration to determine how much ground antenna time is needed to ensure mission success. Recorder data throughput, RF downlink rates per mission timeline, and navigation requirements are aspects to consider in deriving ground antenna costs. Even when the project is not responsible for the cost of ground antenna time, there may be cost associated with the staff performing and negotiating antenna time for the mission.

Mission Operations Staffing Costs

Mission operations staffing costs are driven by the mission, space asset, ground operations, operations concept, and process complexity. These can be controlled by the PM at the beginning of a program to help reduce operations costs. In the costing exercise, the MOM provides the operations staffing profile based on the mission milestones. In some cases, added requirements translate into added mission cost due to testing and verification required. Other cost drivers for mission operations are the number of different operating modes, trajectory correction maneuvers, safe states, anomaly resolution, and mission phases.

Mission Operations Schedule

The MOM provides the mission operations schedule to the PM based on the mission milestones. There are important trades to be made, as requirements, cost, and schedule are interdependent. A change to any one of these will likely have a ripple effect. For example, adding requirements may cause a schedule slip, or necessitate additional staff and thus added cost. A caution here is that a schedule milestone slip due to an added requirement can cause a cascade affect pushing out many more schedule milestones than anticipated.

The operations schedule includes documentation, requirements verification, tool development, command sequence development, testing, simulation, verification and program review, and antenna scheduling.

Mission Operations Requirements

Mission operations system requirements are flowed down from the system requirements document written by the MSE. The number and complexity of the mission operations requirements determine the time required to verify that the requirement is met. In general, the more risk-adverse a program, the more the mission operations requirements. Conversely, the more risk-tolerant the mission, the fewer the mission operations requirements. Careful consideration should be given by the PM when reviewing and signing off the mission operations verification requirements, making sure that they are in line with the program's agreed risk posture. It is acceptable to include verification steps for items that are not requirements but are highly desired. These items should be clearly marked in the Mission Operations Systems Testing and Verification Matrix so as not to be confused with requirements.

Mission Operations Documentation

During the early development phase, the MOM works with the program management team and the engineering leads to determine what mission operations documents are required to support the program. The risk posture of the mission must be taken into account when determining required versus desired documentation. For those missions that are very risk-adverse, it is recommended that a full set of mission operations documentation be developed.

Documentation list for consideration:

1. *Mission Operations Plan*—describes how the mission operations functions will be performed to implement the mission.
2. *Mission Standard Operating Procedures* (SOPs)—describes detailed procedures on how to conduct particular functions within the MOC.
3. *Contingency Handbook*—describes possible anomalies that have been considered and plans for recovery.
4. *Flight Operating Constraints Document*—describes hard and soft constraints ranging from actions the spacecraft physically cannot perform to actions that may be performed at the expense of performance degradation.
5. *Mission Operations Configuration Management* (CM) plan—describes the CM plan followed within the mission operations center for controlling procedures and documentation. This considers the program-level CM plan for higher-level guidance.
6. *Operations Launch Preparation Schedule*—schedule kept by the MOM to keep track of milestones including reviews, documentation deliveries, ground system deliveries, testing opportunities, and so on.
7. *Mission Operations Test Plan*—describes the system-level tests used to test the MOC and spacecraft by putting the spacecraft through postlaunch activities.
8. *Mission Operations Training and Certification Plan*—describes the plan for training and certifying members of the mission operations team.

9. *Spacecraft User's Guide*—owner's manual on how to operate the spacecraft. Should include instrument operations as well if it is a "coupled" mission.
10. *Launch and Early Operations Plan*—describes in detail the activities that will be performed during the commissioning phase of the mission in order to "checkout" the spacecraft and instruments to make sure they are in working order to carry out the primary mission.
11. *Mission Operations System Test and Verification Matrix*—this keeps track of the requirements levied on the mission operations center and status of their verification.

Mission Configuration Management

In addition to the *Mission Operations Configuration Management* Document, the MSE defines the overall configuration management of the mission. A memo is written describing the configuration control board (CCB) meetings, required attendees, what mission elements/actions come under the meeting purview and the software to be used to track items. If there is a difference between the prelaunch, postlaunch, and/or critical program milestones (i.e., encounter, orbital insertion, and so forth), it is defined in this memo.

MOC Location

It is very important during the concept or early development phase to determine/define the location of the mission operations center (MOC). Do not be surprised if one of the tall poles is negotiation for space. There are different requirements based on the classification of the program (i.e., unclassified, restricted, confidential, military, NASA, and so on). Once the location of the MOC is defined, the mission operations team works with the ground systems and connectivity engineering teams to determine the best layout of the space. As soon as the MOC is up and running, space asset testing should be conducted out of this facility. This allows the MOC interfaces to be tested and revised if necessary rather than waiting until closer to launch. The ground system and connectivity engineering teams are the primary focal points for this effort.

Mission Operations System Development

There is a significant effort by the mission operations team to develop the mission operations system to be ready to fully operate the space asset after launch preferably starting with the first mission simulation test. Mission simulation testing conducted from the MOC plays a significant role in validating the mission operations system. The mission operations system includes items such as: real-time script and command sequence development for performing activities required by the subsystem and instrument teams, telemetry viewing displays used by mission operations analysts and flight controllers to interpret telemetry efficiently, standard operating procedures (SOPs) (defined in the *Mission Standard Operating Procedures* document) to perform the various required space asset functions, and contingency procedures (COPs) (defined in the *Contingency Handbook*). Scripts for operating the hardware and software simulators are needed for prelaunch and postlaunch testing.

Mission Simulation Testing

The mission operations team performs mission simulation tests representing various activities that occur postlaunch. These tests are different from those tests performed by the integration and test team and are more representative of how the space asset will be used in-flight. Generally, there are four formal mission simulation tests with the following focus:

1. In-flight subsystem checkout activities including critical milestones (i.e., trajectory correction maneuvers (TCMs), encounter, orbital insertion, and so on)
2. In-flight payload checkout/calibration activities
3. Multiday, around-the-clock, week-in-the-life of normal operations—during thermal-vacuum (T-V) testing—this test generally ends up verifying approximately 80% of the mission operations requirements
4. Launch and contingency test simulations/rehearsals

These test plans are documented in the *Mission Operations Test Plan*.

Operational Autonomy

There are two types of rules that execute autonomously in-flight: operational autonomy rules that execute routinely onboard the spacecraft; and fault protection autonomy rules that only trigger when a fault condition is encountered. The mission operations team develops the operational autonomy rules to support nominal operations. The amount and complexity of these operational autonomy rules vary depending on the complexity of nominal operations. Operational autonomy rules are expected to trigger under nominal conditions. Examples of triggered operational autonomy rules include the following:

1. Confirm successful upload to computer memory
2. Confirm that the sequence loaded to onboard memory successfully engaged, becoming the current executing load
3. Initiate the start of a ground antenna track

Postlaunch

Primary Mission Phase

The mission operations team is charged with monitoring and maintaining the health and safety of the space asset; alerting the mission team when there is an abnormal (anomalous) condition requiring immediate attention; leading the recovery effort to return the space asset to nominal operating condition; developing, testing, verifying all commands being sent to the space asset; developing and maintaining the telemetry viewing pages; and negotiating and scheduling communications with the space asset to accomplish the mission.

MOM Role

The MOM leads the mission operations team. The MOM is responsible for prioritizing the work within the mission operations team, ensuring that the facilities and resources are sufficient to meet the objectives of the mission, addressing any problems within the mission operations team, and working any issues outside of the team that affect the performance of the operations team or space asset. The MOM routinely works with program management, the engineering team, the science team, and the payload team whenever appropriate. The MOM is involved in all program management decisions affecting the operation of the space asset. Additionally, the MOM works with public affairs on any media or tours that are requested to take place in or adjacent to the MOC.

Operations Team Role

The mission operations team is composed of mission analysts and flight controllers. Mission analysts are generally assigned a few focus subsystems and work very closely with the respective subsystem engineer to understand the details of the subsystem including alarm conditions, commanding, and telemetry. Mission analysts develop the commands associated with their focus subsystem(s). Additional focus areas outside of the space asset include the software and hardware simulators. Mission analysts focused on these areas are charged with maintaining the simulator and alerting the software or hardware design team in the event of a simulator problem. The mission operations team maintains these simulators, ensuring the configuration is representative of the space asset in order to provide an accurate simulation of the commands and telemetry onboard the space asset. Mission analysts are often referred to as the offline or planning team. Flight controllers are responsible for maintaining the interface of the ground system in order to establish the communication link with the space asset. They are an integral player in any software or hardware change taking place with the ground antenna system being used to communicate with the space asset. Additionally, mission analysts and flight controllers work very closely with the ground software and the ground facilities teams testing out any changes to make sure that the communication integrity of the space asset is not affected by the change. If a mission is "decoupled," then the flight controller duties become an additional duty of the mission analyst.

Ground Antenna or Track Scheduling

The mission operations team is responsible for scheduling and negotiating tracks to support the activities onboard the space asset. The type of antenna track (i.e., size of antenna, data rate, and so on), duration, and frequency are scheduled based on the activities being performed on the space asset. In order to do this, the mission operations analyst in charge of this effort needs to know the specific rules of the antenna network being used. Many antenna networks require that a general schedule of antenna time be submitted on the order of 2 years in advance with specific details further defined 3–5 months out. Because of the long lead times involved in scheduling antenna time, it is extremely important that the space asset schedule be communicated to the mission operations team as far out as possible so as to ensure that the antenna schedule can support upcoming activities. The mission analyst performing this antenna scheduling function works very closely with the various teams that have requested activities on the spacecraft. The amount of tracking required is a cost driver for both dollars and staff resources.

Real-Time Scripts and Sequenced Commands

There are two types of nominal commanding: real-time and sequenced. Real-time commanding refers to sending commands to the space asset's onboard computer for immediate execution upon receipt. This type of commanding is generally used routinely following launch through the early operations checkout (or commissioning) period. Sequenced commanding refers to sending a group of commands to the space asset's onboard memory for execution at a presubscribed time. When the space asset's onboard clock reaches the presubscribed time, the associated command executes. This type of commanding is used when precise timing is required. Examples of when this type of commanding is used are science observations, track setup, telemetry downlink, trajectory correction maneuver, and so on. It is also possible to implement event-based sequenced commanding, in which a command sequence is triggered for execution by the occurrence of an event such as passing over a particular ground antenna site, detecting an environmental event of scientific significance, or other conditions linked to a stochastic occurrence rather than a specific time.

Command Validation

All commanding, whether real-time or sequenced, need to be tested and validated on the ground before being sent to the space asset. The degree of testing and validation is determined by each mission. In many cases, nominal commanding need only be tested and validated the first time it is used onboard the space asset. Any subsequent uses of the command set do not have to go through test and validation if the commanding is identical and under the same conditions. Critical activities, irrespective of their prior use, are recommended to be tested and validated for each use. Critical activity examples are trajectory correction maneuvers and orbital insertion. Additionally, many missions may require all pointing activities be tested and validated prior to each use to make sure that no pointing constraints are violated.

It is common practice to hold a review prior to each command upload to review the software and hardware simulator results and the commanding. Attendance of these meetings is at the discretion of program and mission operations management, but it is recommended that at the very least, all mission operations analysts contributing to the command activities be present. The MOM leads these reviews.

Modeling

The development of modeling for a particular mission is decided by program management in discussion with the rest of the team. The mission operations team generally relies on a number of software models to validate commanding. These software models check for violations of the various mission constraints ranging from command timing spacing to pointing within so many degrees of the sun. Software models run faster than real-time and as such, can be run many times on a command set without causing delay in the development process. A hardware simulator contains a combination of engineering models or brass boards of each of the space asset subsystems and payloads (if "coupled") as well as software models to mimic guidance and control and other aspects of the space asset for which hardware is not available or practical (i.e., solar panels, nuclear power source, thrusters, and so on). Software and hardware models are indispensable when it comes to

troubleshooting and addressing an onboard anomaly. The amount and fidelity of these models is based on the complexity, cost, mission risk posture, and mission duration/lifetime. The PM may choose not to invest in the cost of a model but should do so only after careful risk assessment. The budget should also address maintenance of these testing resources, possibly including hardware life cycle maintenance (or vender agreements), software upgrades, and license renewal.

Early Operations

The early operations timeline is developed by the mission operations team in close coordination with the subsystem and payload teams. It is built taking into account time-critical activities and other postlaunch requirements. The ground antenna/track schedule is negotiated so as to support the various needs of these checkout/commissioning activities. Many space assets require trajectory correction maneuvers soon after launch. If this is the case, those subsystems needed for the TCM are checked out first.

Early operations checkout of subsystems and payload is performed from the MOC irrespective of whether or not the space asset is "coupled" or "decoupled" and is normally accomplished via real-time commanding due to the ability to control the issuance of the commands based on the resultant telemetry response of the subsystem. All real-time scripts have been tested and verified prior to being executed in-flight, and in most cases, these scripts have been used prelaunch. These scripts are developed by the mission operations analyst in tight coordination with the subsystem engineer. The scripts are built such that they can be stopped at any point for evaluation of the telemetry before continuing. The respective subsystem engineering team representative(s) is in the MOC during the checkout of their subsystem. Mission operations personnel execute the script under the direction of the subsystem engineer.

Routine Operations

Once the space asset has undergone early operations checkout, the mission operations team begins the transition to routine operations. Generally, the early operations phase lasts from 30 to 60 days. The transition period to routine operations is marked by a combination of real-time scripts and sequence command loads with a gradual lessening of real-time scripts such that most commanding executes out of the space asset's onboard memory. Engineering support presence in the MOC transitions to remote monitoring of telemetry from the archive.

Critical Operations

Critical activities onboard the space asset generally require subsystem or payload support in the MOC. The specific subsystem team present is dependent upon the activity taking place. At a minimum, the MSE, autonomy subsystem engineer, planning team representative, flight controller, and the MOM are required in the MOC. Remote monitoring of the critical activity by the subsystem engineer(s) or other required team members is at the discretion of the MOM and MSE. If an anomaly were to take place during this activity, all needed personnel are at hand to evaluate the situation and begin the formulation of a recovery plan.

Off-Nominal Operations

Every mission needs to be prepared to respond to fault or anomalous conditions and have a plan in place to address the recovery. The mission operations team develops a *Contingency Handbook* that includes the possible/anticipated/plausible contingencies and direction for each subsystem and payload. These contingency plans (COPs) can range from a general outline of what to check given an alarm or rule firing to a full up procedure that would be run onboard the space asset to address the contingency. For critical milestones, the MSE undertakes a more detailed analysis of the possible contingencies that could be encountered and develops a risk mitigation strategy. Mission operations personnel as well as other members of the engineering team are part of this effort.

Most missions require formulation of an anomaly resolution board (ARB) to address any critical anomaly onboard the space asset requiring immediate attention. The specific response in the event of an onboard anomaly of this type is developed and maintained by the MOM with refinement based on input from program management and team members (Figures 14.1 through 14.3).

Abbreviations used in the Anomaly process in Figures 14.1 through 14.3:

AR	Anomaly Resolution
ARB	Anomaly Resolution Board
CCB/ECCB	Configuration Control Board
DSN	Deep Space Network (ground antenna network)
	Instrument/payload engineers
MM	mission manager
MOM	mission operations manager
MSE	mission system engineer
NHOps	spacecraft hardware simulator
PI	principal investigator
PM	program manager
POC	point of contact
PS	project scientist
PSE	payload system engineer
SAM	systems assurance manager
S/C	Spacecraft SciOps: science operations

Extended Mission Phase

Most missions have a primary mission end date after which they will propose an extended mission. For mission operations, extended mission could be different from the primary mission in terms of objectives, number of payloads being operated, data downlink rates, staffing, and so on. For national security space missions that operate beyond their planned lifetime, operational lifetime, reduced availability, or operational breadth may occur. While it is not required, it behooves the mission operations team to think toward the extended mission making decisions in the primary phase that would not preclude an extended mission or might make an extended mission more streamlined.

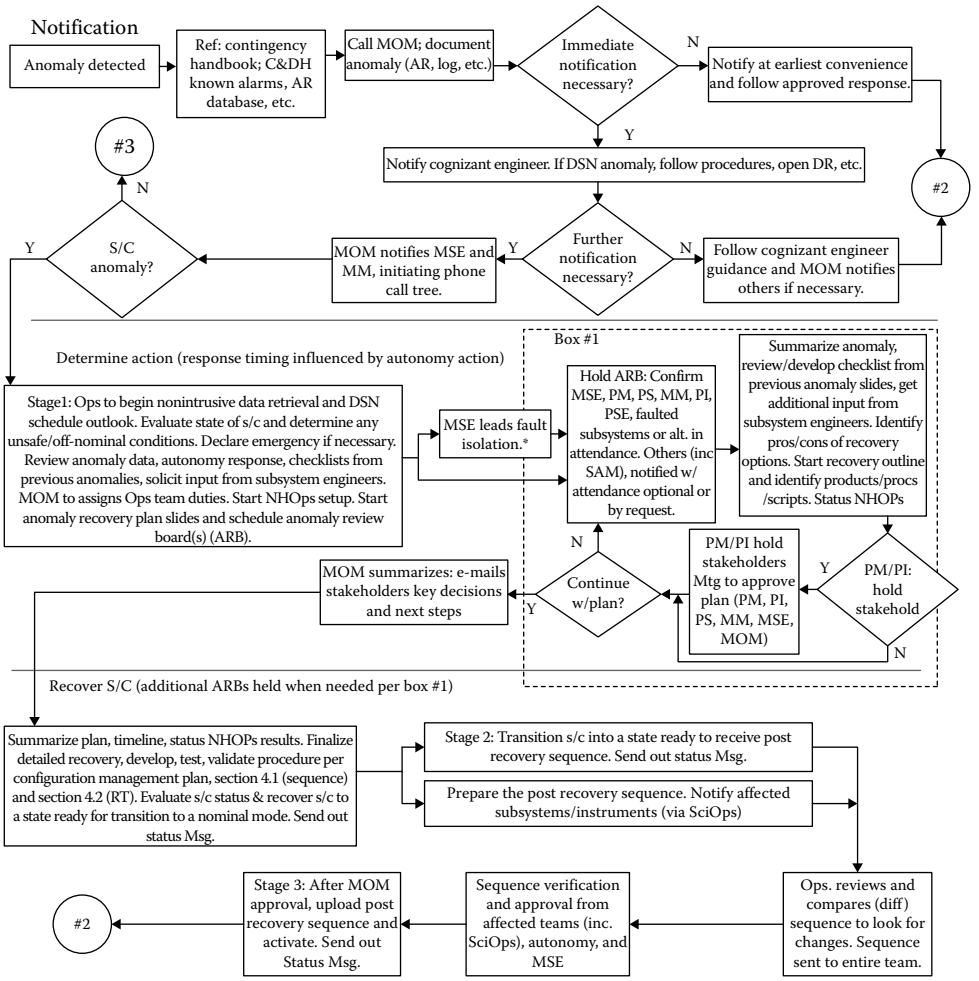


FIGURE 14.1
New Horizons program anomaly process. (Courtesy of JHUAPL, Laurel, MD.)

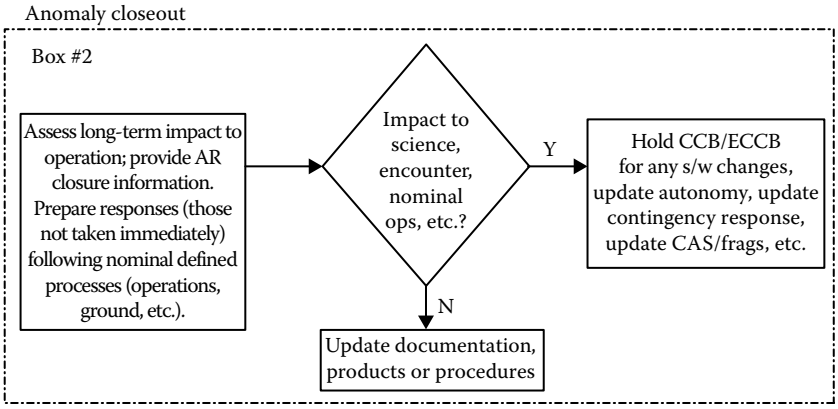


FIGURE 14.2
#2 Anomaly closeout.

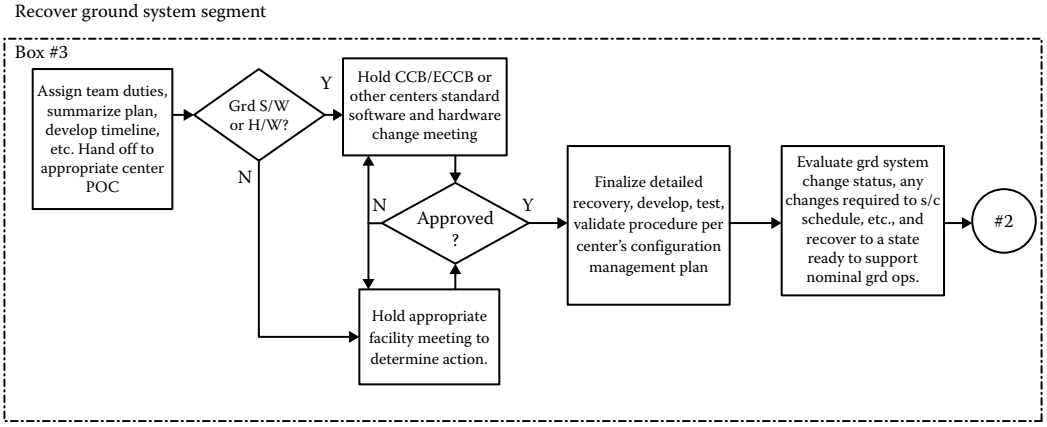


FIGURE 14.3
#3 Recover ground system segment.

Pitfalls to Avoid

1. Include mission operations early in the concept development phase even if it is at a very low level. The feedback they provide on the operability of the space asset design saves costs in the long run and avoids last-minute redesigns. They can also significantly contribute to early concept of operations discussions and documentation.
2. Do not require more documentation or requirement validation than the risk posture of the program.
3. Budget for development and maintenance/upgrades of documents, facilities, processing hardware (for mission lifetimes beyond typical terrestrial technology cycles), software licenses; training, support of critical events, and anomaly resolution.
4. Do not be short-sighted. If the primary mission is to only last a short period of time but the team knows from past experience there is a good chance of being extended, plan primary activity commanding with this possibility in mind. If possible, the mission operations team should develop procedures and command scripts that are generic enough to be used in any phase of the mission. This is also applicable for the space asset design.
5. Avoid adding requirements when they are really nice-to-haves. This will add cost to the mission and will cause a disconnect with the scope of the program. Any added requirements should be carefully evaluated and approved by the PM.
6. Do not save money on flight or ground software only to incur more cost post-launch due to the operations' complexity and manual processing that might ensue. Evaluate the initial costs of this software based on these items. In many cases it is better to incur the cost upfront than to be stuck with a cumbersome process in the long run.


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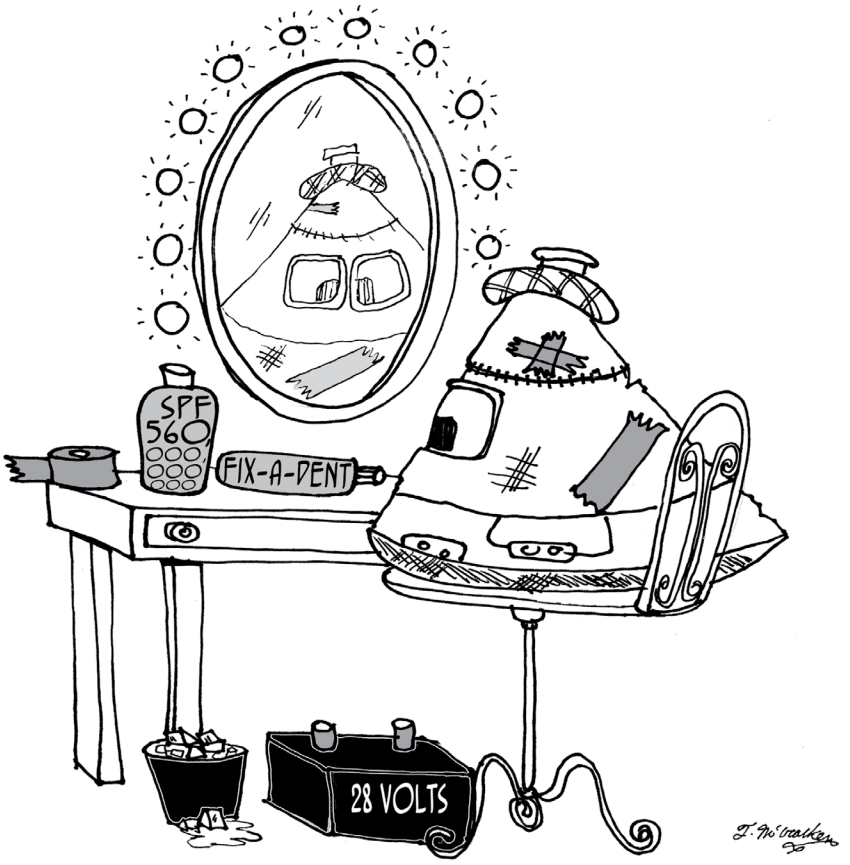
15

Topics in Hardware

Steven P. Thibault

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THE LIFE OF A SPACE CRAFT IS HARD

Introduction

A hardware emphasis is essential for aerospace project management because at the end of any successful aerospace development it is high-quality, fully-performing hardware delivered to its operational environment that is the most fundamental objective and at a cost that is affordable, or at least fundable, and schedule that maintains the hardware's relevance. This focus is true whether the business domain for the hardware application is civilian, military, or commercial space. The scope of quality/performance, cost, and schedule will likely be different for each sector, but the result of hardware is invariant. A comprehensive understanding of the hardware development phase is an essential attribute of successful aerospace project management. This chapter explores key aspects across the diverse types of hardware comprising aerospace systems and development influences essential to good hardware delivery (Figure 15.1).

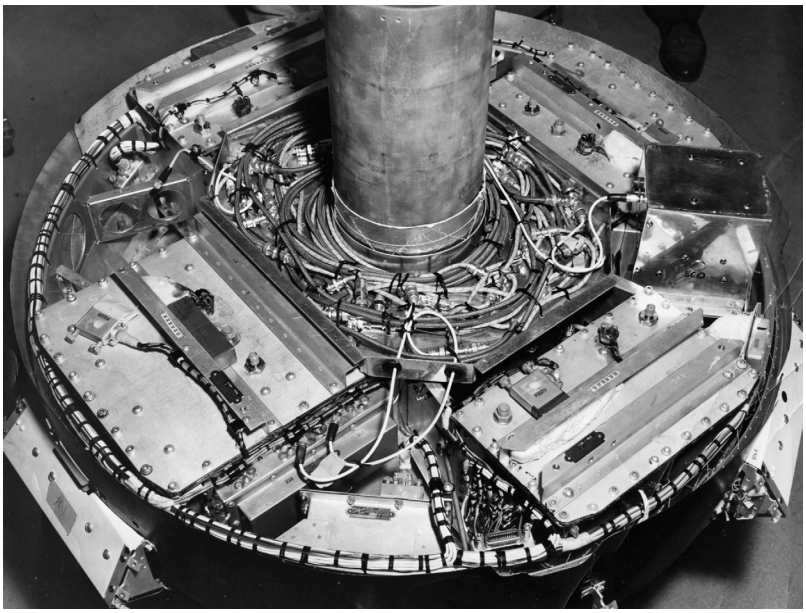


FIGURE 15.1
Transit 1—a spacecraft hardware in 1959. (Courtesy of JHUAPL, Laurel, MD.)

Product Definition

At first glance, it is a clear statement that the definition of the hardware to be delivered needs to be specified; however, too often only the primary components within the major subsystems are identified. It is true that the primary elements principally define the overall hardware costs and schedule, and notably the critical path. This certainly warrants the project manager's (PM) priority attention as the project team designs the primary structures, procures primary subcontracted items (e.g., propulsion, solar arrays, batteries), and designs the electronic components to perform the mission requirements. Also, every element needed to complete the aerospace system must be identified within the overall product, estimated for cost and schedule, allocated within the overall integration and test effort, and assigned an owner to complete. And this must necessarily include identifying all technology development, prototypes, engineering models, and the critical equipment in addition to the flight hardware.

Too often in the aerospace industry, once the principal framework of the product structure is defined, the detailed components are dismissed to the attention of a subsystem or box lead engineer and not fully appreciated by the management team. In this manner, the product definition is built from the bottom-up as the engineering team specifies the lowest level of assemblies and progressively thinks of the integration of higher levels of assemblies as the overall development progresses. For the circumstances where the engineer has not thought comprehensively, or has difficulties completing hardware deliveries, the final hardware development can experience significant upheaval in cost and schedule. This results in stress, for the smallest components; for example, a tertiary structure was not

identified to offload a waveguide run to withstand the launch vibration environment; a circulator was not procured to balance the communication performance; a thermal closeout was not accommodated for a critical outgassing and vent path; or a critical piece of custom ground support equipment was not identified but was needed to complete assembly or test. Finding such omissions late in the project schedule results in the highest cost, that is, development team is at its largest, or use of precious schedule reserves or delays if the next level of integration cannot be completed until the late hardware is delivered. Final determination if the hardware is complete proves difficult because completion of the bottom-up definition may be incomplete and the engineers able to answer such questions are overburdened with simply trying to solve the problems.

It is essential that the entire product structure be defined top-down and then revised bottom-up as the detailed design is complete. This is best done as a physical decomposition for hardware because the product is built physically with a mix of people and machines performing the fabrication, production, assembly, and integration tasks. The core engineering team should work together to define the entire product structure and then place it under configuration management as all other drawings and designs.

It is important that the PM ensure that the entire hardware development, procurement, and fabrication are scoped, planned, implemented, and tracked. Initial product definition down to the board, frame, and bracket levels should be placed under configuration management at the preliminary design review. The final as-designed product (detail drawings for fabrication and integration) and final product definition should be released at the critical design review (CDR). With a complete product definition at CDR, any designs that are lagging are readily apparent and can easily be tracked by the PM to final release. With a complete product definition at CDR, the entire hardware implementation can be tracked by the PM through delivery to each next higher assembly; which in some cases (e.g., solid rocket motor explosive transfer assemblies [ETA], liquid propellants) occurs at the launch site. Appropriate attention by the PM to the entire build results in a proactively managed delivery and avoids costly reactionary responses to forgotten pieces.

Product Design Freeze

Design decisions for interfaces and drawings need to be made and need to be enforced. Allowing excessive flexibility in design changes always results in hardware delays, which affect both cost and schedule. In the middle of the detailed design phase, it can be difficult to understand the longer-term effects of allowing design freezes to slip. The loss of days in this phase simply feel like a loss of days, but in truth, it can be months in the overall schedule. Clearly specified design freezes need to be identified as part of the critical development path and need to be tracked with the same rigor as technical budgets. The tendency to allow one more iteration, one more trade, one more analysis, or lower-level delays must be avoided.

A series of design freezes can be established to rough in the primary drivers, for example, mounting of the propulsion system and launch vehicle adapter, and then allow future refinements, such as final heat pipe races and insert locations. Fabrication schedules and many subcontracts are based on mature and stable interfaces. Changes or delays in the specification will always result in cost and schedule growth. It is essential that the PM

understands the critical design freeze drivers, include them in the master schedule, and track as critically important milestones. By not establishing and maintaining such rigor, interface issues are probable, and schedule delays are certain.

Effectivity and Design Updates

For all first-time builds and immature product lines, issues are going to be discovered through design and peer reviews and problems will be encountered during the hardware implementation. Often for expediency and immediate focus of the program team, there is no emphasis on cleanup of design drawings for changes made to make the design work for the specific implementation. In the satellite industry where heritage has high importance for contract award and product selection, rebuilds of valued elements of the first-time design will certainly occur. Every attempt should be made by the PM to ensure, and fund, clean, finalized, as-built design documentation with all updated revisions and control of the product configurations. This certainly should be a lower task priority unless the number of changes to a specific design and the documentation approach of such changes pose risk of confusion to the implementation or verification staff. Errors due to the misunderstanding of design documentation must be avoided. When the engineering team has delivered products to the next higher assembly, time is often available to quickly and efficiently update designs.

Effectivity of design changes or, in other words, changes that may only affect a specific build should receive consideration at the time of accepting the design changes. Too often, the approach will be digital on a project; that is, effectivity is 100% to all builds or 0%. Modern engineering resource planning tools allow efficient tracking of design relevance to specific product serial numbers, so the added effort to have the approval team consider relevant effectivity is small. If an organization has a central engineering design authority for product lines, then they should be consulted for the effectivity of future builds. Assigning effectivity only as needed helps to minimize overall cost and ensures sustainment of product versions that each may have future value.

Long-Lead Procurements

All aerospace development schedules are paced by long procurements; especially in the competitive government and commercial markets. Ultimately, all parallel efforts merge into a serial line flow of system assembly, integration, and test. Developing a schedule forward with design durations and perhaps funding constraints for the significant milestones and then working backward from launch dates, or shipment dates to the launch site, through the system integration and test, subsystem assembly and test, and component hardware fabrication will surely identify part procurements schedules that do not fit. These items become the procurements that need to occur before completion of the final design and are universally referred to as long-lead procurements.

Estimates on these procurements need to be identified in the formulation program phase, which may be a competitive proposal. Early procurements pose some risk for a new design as the capability of the part needs to be specified before the design is complete. This then may become a constraint on the final design implementation because there will be insufficient schedule to procure alternative parts. Additionally, quantities of parts need to be specified to estimate the total cost and ensure the final fabrication plus spares needs can be met. The final quantities must include breadboard, prototype, engineering model, and ground support equipment/test bed development, the flight quantity needed, and spares for production attrition and the possibility of rebuilds if problems occur anywhere in the system development life cycle. The costs can be sizeable and, for government programs, often require preapproval for programs to make procurements early in concept development and preliminary design phases (Figure 15.2).

The importance to the PM lies in ensuring that the engineering design team, and specifically parts procurement planners, are identifying all long-lead procurements to put into the overall program cost and schedule plans. Additionally, during early execution of the design phases, it is essential that the PM track the decision milestones for the long-lead procurements and ensure all procurements are placed in time. Some lead times can be in excess of 12 months if new material dies are required. During the time after the procurements are placed, there is a tendency to ignore the progress, or lack thereof, being made by the particular vendors. Too many programs have been unnecessarily surprised at the end of a long-lead schedule that the needed parts have been significantly delayed or perhaps even failed a mandated qualification or screening test. Regular contact with all vendors needs to be defined that is both efficient and rigorous to ensure that parts will arrive when needed. Each PM should establish tracking mechanisms that are appropriate to the product complexity, experience with vendors, and strengths of the particular development team. Simple methods that have proven effective include requiring photographs of progress to accompany weekly or monthly progress reports, and occasional, random visits to vendor facilities for informal meetings when other program activities are occurring in the local vendor region.



FIGURE 15.2
Bonded stock room for flight-grade electronic parts. (Courtesy of JHUAPL, Laurel, MD.)

As mentioned earlier, part quantities are determined by development, flight, and sparing needs and philosophies. Over the course of a hardware development, these decisions should be revisited based on the execution of the program and its risk posture. Recognizing the long duration of several of these procurements, bulk buys are very attractive in particular for a product line or a part that is likely to be used in subsequent designs or builds. Corporate investment considerations in a part type and establishing an available inventory can have significant benefit in overall competitiveness and ability to deliver products on cost and schedule.

Long-Lead Subcontracts

Long-lead subcontracts require the same need and attention as long-lead parts procurement but at a higher cost and longer schedules. Many spacecraft programs have the critical path through the propulsion tanks fabrication to receipt of the core structure through the assembly of the integrated propulsion system and delivery to spacecraft integration and test. This sequence can easily require 40%–50% of the schedule. Other long-lead subcontracts are often flight battery development, high power traveling wave tube amplifiers, solar arrays, deployable antenna reflectors, and instruments or payloads if directly subcontracted by the mission. If the critical path does not contain one of these drivers and dedicated schedule margin against all deliveries, then the schedule should be thoroughly viewed for errors and perhaps specific schedule quotes obtained from key vendors to confirm confidence in the overall schedule. And of course, subassemblies for instrument development, in particular for new detectors or sensors, can exceed the spacecraft bus lead times and need to be considered.

Because the cost of these subcontracts is high, there are several important considerations that the PM must observe. First, requirements for these subsystems must be well defined and often earlier than the preliminary design phase. A program may spend its first few months in requirements and specification definition and contract negotiations to meet price and schedule targets. These requirements need to be viewed as anchor points for the future spacecraft design effort, because changes will both be costly and schedule eroding. Second, the funding profile of an aerospace contract may have termination liability limits so only portions of the subcontracts may be achievable. This then drives follow-up contracting efforts, which may include updates to requirements, specifications, and statements of work and renegotiations for the final total award. These efforts need to reside prominently in the development schedule and must be staffed adequately to ensure that delays in these milestones do not result in hardware delivery delays.

Third, once these key procurements are made, the PM needs to be mindful to maintain rigor in the engineering process, resisting the temptation to refine the design in ways that result in significant subcontract cost growth and ensure that all information exchange milestones are met regarding the subcontract schedules. Depending on the size or risk of a particular subcontract, a separate manager in addition to the lead engineer may need to be assigned to ensure success. In extreme cases, a dedicated manager, or a quality representative, may need to be assigned *in situ* at the subcontractor facility to ensure success. And if the subcontract is international, schedule considerations need to be included for technology and export/import legal requirements; including on-site support at the spacecraft facility if needed and the possibility of return shipment for repair.

Finally, the PM needs to be mindful of where the final engineering knowledge resides for each subcontracted item and how to access it for key phases and/or problems during spacecraft integration, testing, launch campaign, launch, and mission operations. Options include time and materials subcontracts to the original vendor for engineering services or assigning internal staff that acquire the essential knowledge that would be needed. And as with any critical development, regular oversight of schedule and cost performance is essential for all subcontracts and final hardware delivery.

Parts Derating, Screening, Qualification, Lot Jeopardy

The fundamental inability to repair failures in aerospace products or the immensely high cost to do so for the limited systems that can be repaired in orbit drives attention to quality, which routinely then drives costs higher. Industry interest in smaller systems that can be built more cheaply to then launch more into orbit may offer a paradigm shift, but it has not yet occurred and for some national priorities it may not be desirable for operational robustness or meet operational needs. As designs emerge to leverage the advances made in commercial electronics to deliver higher performing capability, parts derating, screening, and qualification become essential to ensure the parts will perform as intended and as long as intended in the operational environment.

Parts derating, that is, operating at levels below the maximum rating of a part is essential to ensure performance in light of materials and workmanship variation, unexpected stresses due to unplanned operational modes, and differences with the actual and modeled environment. The implication to the part is ensuring that sufficient margins exist in its operation with respect to temperature, inrush current, maximum operating voltage and current, and duty cycle, to name a few considerations. The derating analysis is a nexus between the parts engineering team, who understand the capability of the part, and the design engineering team, who understand its application. The aerospace PM needs to understand the joint responsibility here and ensure that derating analysis is completed timely in the design phase. Parts that exhibit insufficient margin may require additional testing to ensure successful performance or substitution to a more capable part. Such results present both cost and schedule risk to a project, both of which increase if issues are found late in the program development and so the process should start early.

Electronic parts acceptance screening and qualification and, to a significantly lesser degree, materials, often require significant test duration in specialized facilities. Many development schedules cannot accommodate both the long-lead parts procurement duration, long acceptance test duration, and/or long qualification duration to meet the overall launch schedule. So the risk is weighed as test requirements are specified for part lots, screening samples for the whole population, and sample qualification testing. If a part is authorized for use in electronic board manufacturing before all of these tests are complete, the program carries a certain risk that if a failure occurs during qualification, then costly and time-critical rework and possibly alternative part selection may be required. The acceptance test, which confirms performance against the mission levels, must be complete prior to using the part(s) in manufacturing, whereas the qualification testing, which confirms performance margin, is allowed to continue in parallel with development. Across the industry, this authorization to use a part with incomplete testing is often

referred to as "lot jeopardy" because there is a jeopardy that the part lot may be found unworthy for flight use.

Lot jeopardy should be viewed by the PM as a risk. It is essential that the PM remain cognizant of all lot jeopardy decisions, which need to be made with input from the technical and quality team, and assess the risk to schedule and cost for each instance. There may be times that a program can provide a blanket decision to accept the use of all parts for fabrication with incomplete qualification, but this should be judiciously evaluated with the design engineering team, component engineers, and history of the part. Additionally, immense labor expenditures are possible to close issues later in the program and can be unexpected distractions to the engineering team's priorities to complete testing for the higher level of assemblies. As far as possible, lot jeopardy should be avoided. When it cannot be avoided, the PM needs to ensure that the appropriate parts team is rigorously driving the issues to closure. Specific tracking and attention to progress need to be ensured. Acceptance of all parts, or rather parts that have open acceptance, should be evaluated at all major hardware fabrication, assembly, integration, and test reviews to ensure a clear understanding of program risk.

Specifications, Standards, and Government-Industry Databases

Industry specifications and government standards are essential resources for hardware development from details of parts screening and qualification to environmental test requirements. The aerospace PM needs to ensure an understanding across the program of the specifications and standards to be used as contractual, applicable, or reference-only documents and the precedent hierarchy if there are conflicts in the documents. This understanding needs to occur early in the program to ensure that sufficient cost and schedule have been allocated. Also, as acceptance of the product occurs from the lowest assembly to the integrated product, compliance to the specifications and standards will need to be demonstrated to satisfy customer acceptance of the product.

Parts and material databases are important resources to aid the success of the program. One in particular that is available in the United States is the Government Industry Data Exchange Program (GIDEP), which is a valuable cooperative activity between U.S. government and U.S. industry participants to ensure the quality of products resulting from issues or risks of parts, materials, and processes. Through a centralized database, programs can become cognizant of any issues that may have arisen on other programs on parts that they are also using. With this knowledge, specific evaluations can be made of the part or material application to determine if a current problem exists or a future problem may occur.

Due to the immensity of the number of parts and materials on an aerospace program, it is essential that an active GIDEP program is in place for value to be gained. The PM should ensure that an appropriate organization is in place and funded to process GIDEP reviews against all program parts purchased as they are put in inventory. Since a GIDEP alert can occur at any time, periodic evaluations at major fabrication and/or integration reviews should occur to understand any issues or risks that may have occurred. And depending on the duration of a mission, the periodic review may have merit for a spacecraft in orbit to assess if any operations changes may be needed to ensure continued operations. The GIDEP process is another form of risk identification and mitigation available to a program. On many government contracts, it is a requirement, but it has value to all programs when implemented in a cost-efficient manner.

Material Procurement

Significant program attention is more often applied to electronic components (and their environments, which often includes radiation) because most aerospace system developers design and fabricate core electronic components of the system. Materials and processes (the use of those materials) and the safety of the materials, notably at the launch site, are no less important, and the PM needs to ensure a sufficient level of visibility regarding the design, selection, use, and qualification of materials across the aerospace system.

Often for conventional spacecraft designs and applications, concerns for materials can be limited to specific workmanship and traceability of where the material is used. If material, such as an epoxy, is found to be suspect in subsequent sample hardness tests, then it is critically important to know where it was used across the spacecraft to be able to evaluate the performance risk in each application. It is also essential to ensure that certificates of compliance for each material procured has been reviewed and archived to facilitate any future failure analyses that may be required and have a material contribution. And certainly for solar arrays and propellants, material quality and acceptability of the application are critically important.

For spacecraft with sensitive optics, detectors, or high-voltage grids, material acceptability is essential. This is often categorized under the general area of contamination control, but it is an important engineering function beyond the general perception of keeping the spacecraft clean and periodically cleaning the spacecraft. Material contamination can be manifest, for example, as outgassed material in the environment of the vacuum of space, high-temperature exposures, or material debris becoming collected in unwanted locations on the spacecraft and instruments. Prevention and mitigation often require detailed analytic modeling to understand the issues, material tests and qualifications, and workmanship verification of the design implementation.

For special aerospace missions that are pushing applications in extreme environments or striving to improve performance, such as high power communications, solar cell efficiency, or battery capacity performance, materials science and engineering can become essential technology developments. These endeavors present special risks, and associated costs and schedules, which must be well planned within the project and have alternative approaches to maximize the ability to achieve success. The PM should be cautious with any materials development and ensure a program approach that ensures sufficient maturity at the completion of the preliminary design.

In general, the essential contribution of the PM in this domain is recognition of the important need of a materials and contamination program that includes appropriate modeling, comprehensive review and approval of all materials across the spacecraft, and strong workmanship and inspection processes to ensure success. Key milestones should be included in the overall schedule, and attention to completion is required. Risks should be considered if delays occur in approvals or any qualification tests.

Production

Production should be viewed as the most exciting time on any development project because it is the time that all of the creative energy in concept development, design, and analysis is being realized in actual hardware. It can also be a phase of immense stress because whereas

many things can appear to work successfully on paper, or in electronic models, in production the designs now must be made to work. Too often, a team that is well skilled for design and development may be inexperienced or ineffective in actual hardware build and test activities. Additionally, too often, insufficient attention is made to adequately plan for the hardware manufacturing phase and problems arise that could have easily been prevented otherwise. The aerospace PM must provide effective leadership in production planning during the design phases and in implementing and realizing the product in hardware. Large programs sometimes choose to identify a dedicated deputy PM for the product realization as the other equally important task of preparing for the actual mission operations remains, and likewise requires, PM attention.

The different types of production require different attention and are treated separately. Electronic box fabrication, mechanical fabrication, and specialty hardware are addressed here. Aerospace integration and test, which is the final hardware product realization, is treated in its chapter.

Electronic Box

Most aerospace organizations have at their core proprietary electrical system architecture and internal production capability. The particular mission offering comprises a configuration of the electrical bus with sensors, communication devices, actuators (e.g., reaction wheels), and batteries appropriate to the need. These latter components are procured from qualified vendors, and their management follows the long-lead subcontracting guidance, though some may not be long-lead. This section discusses the common internal electronic box product realization.

Depending on the complexity, size, and redundancy of the spacecraft, an electrical architecture can comprise 4–40 boards, commonly called printed wiring assemblies (PWAs). The low end of the manufacturing extreme provides little stress to a production organization, but the high end can inundate the capacity. The PWAs are appropriately categorized as separate subsystems, for example, command and data handling, power, telecommunications, and attitude control, as they require different engineering specialties. The development lends itself to capable matrix organizations and often segregated production planning. If this is the case, it is essential the PM ensures adequate attention is applied to production planning. If the product is a new design, one-off, or proto-flight, then it is even more critical that planning is assigned priority because everything will likely take longer than envisioned, rework will be required, and competition for precious manufacturing resources will be fierce. If the product is a repeat build of an actual product line, the manufacturing organization has independent management that regularly plans its throughput and capability.

Some important topics that need careful consideration well in advance of the start of fabrication are

- Distributed planning versus integrated or centralized
- Requirement for independent verification of printed wiring board coupon quality
- Production versus proto-flight
- Surface mount versus hand-soldering

- Interleaved engineering testing to confirm design and workmanship, final approach to conformal coating, capacity for rework
- Approach to box assembly and subsequent performance and environmental acceptance testing
- Handling of deviations and nonconformances

As electronic boxes often have software, field programmable gate arrays, and application-specific integrated circuits, the integrated development of these systems must be considered. Many of these areas will require staff, cost, and schedule considerations, so sufficient program reserves must be assigned in the program formulation and preserved for this hardware phase.

The aerospace PM is not expected to be a subject matter expert in any of these areas affecting the electronic box production, but rather must recognize the complexity of this product realization and ensure sufficient planning occurs. In this part of the hardware phase, days become important. Other than a fundamental design flaw or unexpected failure or damage, schedule is lost a day at a time in the phase, so the entire project needs to be primed for efficient issue dispositioning and decision-making. There may be a tendency to avoid yet one more meeting, but efficient meetings and communication paths are essential to an efficient and on-time electronics production. Shifts and weekends and surge capacity need to be planned, prepped, and funded in advance of need, otherwise they are likely to be unavailable. Targeted schedules for specific needs outside of the master program schedule may be essential to success. In fact, the manufacturing center must have a resource-loaded schedule of their domain space to be able to perform effective planning and provide confidence to the PM of delivery expectations.

Mechanical

As previously discussed, the primary structure and propulsion system often represent the critical development path and thus generally receive adequate planning attention. Difficulties only arise if overall system mass becomes an issue or design freezes do not occur when required. Mass requirements often drive toward composite structures, which can require significant manual fabrication time. Load cases may not be defined early enough for propulsion integration needs, so there is a risk in the design of light mass tubular struts. Whenever prototype testing can occur for a new or significantly modified design, it should be endorsed by the PM and sufficient funding and schedule must be allocated. Finding a structural design flaw at static load test for the assembled structure, or worse at system vibration or acoustic testing, can consume all available reserves.

Solar arrays provide a unique electrical and mechanical interaction in the design process that needs to be recognized. In general, extra power is achieved by the addition of additional solar cells, which increases mass, which subsequently demands solutions for light mass arrays and deployed booms. Early robust power budget sizing is essential to meet solar array delivery lead times. For extreme mission environments, extensive qualification testing and/or life testing may be required to ensure the success of a specific design. Procurement and laydown of solar cells are almost universally subcontracted and for some missions, it may require a long-lead subcontract. All of this needs careful consideration by

the project, including the approach to final solar cell inspection, preparation, and perhaps repair at the launch site.

For certain missions, notably geostationary (GEO) communications systems, antenna reflectors can pose immense developments because of complex-shaped and gimbaled reflectors, which are becoming commonplace to maximize the mission performance. And overall reflector size is increasing to such sizes that mass becomes a significant consideration. All reflectors require RF pattern characterization to ensure that the performance requirements are met in addition to assembly-level environmental tests, normally thermal vacuum and acoustic testing. Sufficient planning and oversight are required by the project to ensure development success, similarly, to solar arrays as the engineering responsibilities span two domains: mechanical and radio frequency (RF).

Everything needs a bracket and often gimbals for some payloads. This is a simple statement, but too often overlooked. Thrusters need brackets that can allow alignment. Propulsion tubing needs brackets to traverse the distance between the propellant tanks and thrusters. Harness cable and coax runs need brackets that accommodate testing. Waveguide needs brackets to traverse the distance from an antenna feed horn to a receiver or transmitter. The solar array and antenna reflector deployment devices need brackets. Equipment panels need mounting brackets. Launch vehicle power and separation services need brackets. Despite this ubiquitous need, few project schedules call out bracket design, development, and fabrication. And most projects experience some unexpected mechanical cost growth for bracket development and schedule replanning for late bracket identification and subsequent delivery. The aerospace PM can aid the program execution immensely by establishing placeholders in all subsystems for all secondary and tertiary structure.

Telecommunications Specialty Hardware

Specialty hardware for telecommunications will certainly have a different definition for each mission and the particular strengths of the developing organization. Common types of hardware that fall into the area are waveguides, coaxial cables, and switch assemblies. These items are best procured by vendors that deliver high volume, quality hardware due to the uniqueness of the fabrication techniques and the criticality of qualified processes. For example, waveguides are lightweight transmission paths of RF energy requiring continuous conductive deposition on the interior surface and high-pressure flanges that traverse multiple joints across the spacecraft. Too often, lower-cost and shorter schedule alternatives are sought, resulting almost universally in unexpected problems and reactionary responses to meet schedule. The aerospace PM, in general, is best served by paying for a qualified product and looking for project savings elsewhere.

Additionally, every waveguide run is unique to the mechanical placement of all components and the integration approach of the spacecraft. Designs of the mechanical assemblies and the secondary structures to support them need to begin early and have the priority attention of capable staff. The PM needs to ensure that adequate fidelity is included in the schedule for these piece parts to make sure that they are not overlooked. The use of mockups and accurate wooden models to verify sizing, placement, and runs, and to establish the integration feasibility of designs have proven to be a cost-effective means to reduce risk of problems later in system assembly and integration.

Solid Rocket Motors Procurements; Safe and Arm Device, Explosive Transfer Assemblies

Few spacecraft missions need to concern themselves with solid rocket motors, but as they have special considerations for a PM, a short discussion is included here. The significant hazard posed by the solid rocket motors (SRMs) and ancillary equipment present particular needs and adds requirements for simulators involved in spacecraft-level testing. Producing standard SRMs can require 14 months, so completion of the requirements is often not as pressing as other subcontracts on the critical path. In fact, the SRM is never integrated with the spacecraft until late in flow during the launch campaign. For a new motor development or even a refinement to existing motors, such as stretching the case, significant development time is needed and requires a dedicated effort.

It is essential to ensure that all items are captured in the subcontract: SRM and igniters, ETA, safe and arm device (S&A), heaters and temperature sensors, thermal blankets, all handling equipment, installation tools, shipping containers, and personnel to perform all launch handling operations. Also, launch processing requirements may require cold soak and x-ray measurements, so facility capabilities must be confirmed and verified before equipment arrival on site.

As the SRM represents a significant mechanical and thermal load in the spacecraft system, careful consideration must be given to simulators, analytic approach, and test verifications. All of these activities need identification in the overall program plan and need oversight equivalent to every other subsystem.

Thermal Procurements: Heaters, T-Stats, Temp Sensors, Multilayer Insulation

For the longer schedules of scientific spacecraft, thermal procurement schedules are not an issue. However, for the more aggressive commercial GEO communications plans, the precision of bi-metallic thermostats may cause schedule pressures due to the timeline required for delivery. The tendency to specify heaters, blankets, and thermostats later in the development flow should be resisted. In particular, for applications requiring heat-pipe embedded equipment panels, the thermal design needs early attention as it directly impacts the mechanical structure delivery (Figure 15.3).

Thermal hardware is robust, so significant sparing is not typically required. Sufficient blanket material should always be procured for the multilayer insulation (MLI) as wear and tear on the blankets can be severe during spacecraft assembly, integration, and test.

Two main aspects of the thermal subsystem for the aerospace PM is designed validation and workmanship verification. It is essential to have comprehensive system thermal vacuum balance tests of bounding environmental and operational cases to validate the analytic model. This is often referred to as model correlation. As it happens late in the development of the spacecraft system, PM attention is beneficial to ensure that the model correlation does not languish. For production spacecraft, this timing is fine. For prototype spacecraft, stepwise validation is worth considering as any issues found late can become critical. Specifically, an early propulsion system thermal balance can be accommodated confirming both its design and workmanship. The benefit of completing at this time is that



FIGURE 15.3
MLI on new horizons spacecraft, October 2005. Ten years later, this craft flew by Pluto! (Courtesy of JHUAPL, Laurel, MD.)

the access to the thermal installation is far superior than it will be for the integrated spacecraft. As the propulsion system is often on the critical path, taking this approach needs to be decided early in the program formulation. Because the full verification of the thermal system occurs at the system-level thermal vacuum, it is important to have functional verification as thermal elements are installed. In addition to a robust plan for modeling and test, the complexity of spacecraft thermal systems require carefully enforcing performance margins to address measured results that stray from expected model predictions.

Hazard Procurement

Hazards such as propellants and radioactive sources for instrument calibration need to be considered. Propellant procurement presents no significant management concerns unless international launch campaigns are planned. The U.S. launch ranges provide propellant procurement and loading services and, with regular launch schedules, everything is well-maintained. Services can often be secured through the launch vehicle services. The subcontract needs to include support for the spacecraft vibration testing to ensure any peculiarities of the propulsion subsystem design on propellant loading and pressurization are understood early. Calibration sources can be particularly challenging depending on the need, so early attention is essential.

International launch campaigns span scenarios where propellant and loading services are provided through a subcontract to situations where the spacecraft provider needs to provide propellants, loading equipment, and safety equipment. The latter case, of course, requires significant management attention as shipments require ocean transport, as well as

significant government coordination and approvals. It is clear that coordination and delivery should occur early to the launch sites to ensure no risk to the overall launch campaign. In the commercial sector, international launch service pricing is attractive, but it must be evaluated with all additional costs required such as identified here.

GSE Procurement

Spacecraft are designed ultimately for their operational environment, which begins with being fully assembled and stowed on the launch vehicle for launch and transitions to full operational deployment in orbit. Obviously, the orbital environment is dramatically different than that of Earth, notably zero gravity, and thus significant mechanical equipment may be required to assemble and test the spacecraft. Additionally, major electrical and telecommunications equipment are required to validate the system designs to simulated environments and verify overall workmanship.

Early planning is essential to identify all major articles of equipment, assess procurement versus design and fabrication options, labor requirements for internal design and analysis, need dates, and cost. Too often, equipment is identified only after the flight hardware is already designed and in fabrication, resulting in unplanned costs and schedule risk. Equipment lists need to be identified for each subsystem early in the formulation phase with cost estimates and margin on schedule. Equipment development should not take priority attention away from the flight development at the PM level, but there needs to be adequate oversight to ensure the flight development schedule is met. Certifications, equipment verifications, and proof tests need to be identified and included in the margined schedules. When equipment deliveries begin to present risk, then the PM should apply active oversight.

Large equipment procurements should be considered strategically by every organization. Capital and facility investments can provide a significant advantage to a flight development program and reduce the active task list from the program. If a program schedule is dependent on a capital investment, then the PM should ensure sufficient and periodic oversight to guarantee the assets are available when needed. Everything needed to complete a flight hardware development should be a concern at some level to the program management team.

Subcontract Topics: Scope Changes, Mandatory Inspections, Shipping

PM attention and oversight of hardware subcontracts is essential regarding scope changes to ensure cost control and hardware delivery schedules. At times, engineering interaction occurs that may unexpectedly be perceived by the provider to refine the statement of work (SOW), requirements documentation, or specifications and are interpreted as subcontract direction. “Gives and takes” lists are another manner in which changes are informally allowed. If left unbounded, both approaches result in unknown risks that may not be realized until hardware deliveries and review of final product performance.

Timely updates to necessary subcontract scope must occur to ensure the rigor of the subcontract and commitment process. Internal development needs of the prime organization often garner most of the regular management attention, so extra care may need to be applied to ensure timely updates. The emphasis with the engineering liaisons to each subcontract needs to be consistent as it relates to proposed scope changes to aid in clear vendor communication. Agreed-upon deliverables need to be maintained to establish habit on the contract execution, providing the best opportunity for hardware delivery to be fully compliant and successful to the specified requirements.

Hardware Schedules

Successful aerospace management requires an integrated master schedule (IMS), which are often thousands of lines long. The IMS serves numerous useful functions for overall program management and cost and schedule performance assessment. It is an essential management tool and is discussed in Chapter 4: *It's All about the Plan!*.

The IMS should not be confused with or replace specific hardware production schedules. It should be expected that each specific production organization, sometimes referred to as work centers, maintains specific schedules comprising the lowest level of details to produce the hardware and loaded with resources to ensure schedule credibility. There may be a tendency to add this level of detail to the IMS, but this only serves to create a master schedule too complex for efficient replanning. In any hardware production, replanning will occur and is essential when problems or delays occur. These individual schedules provide an essential value and it is the responsibility of the hardware production organization to keep the status accurate and synchronized with the program-level IMS. Effective synchronization often proves to occur by anchoring the various hardware schedules through the IMS at hardware development milestones; thus, detailed refinement can be managed in the hardware schedule and only relevant impacts affect the IMS.

Nothing prevents an organization or individual from generating and tracking a detailed schedule to aid their production delivery, and no specific authorizations are required to do so. In fact, an aerospace PM should encourage each hardware organization to establish their detail schedules and periodically review the detail to see that it continues to align with the program IMS. When dramatic replans are necessary, then these specifics should be included in the IMS such that it continues to serve the overall program management requirements.

Perils and Pitfalls

There are four significant perils in the hardware development phase of aerospace program management: (1) inadequate early planning for the production, (2) inadequate rigor to the design completion, (3) being able to recognize when "good" is good enough, and (4) inadequate hardware schedule tracking during production. Each poses significant risk to cost and schedule and combined can be disastrous to successful program completion.

The preceding sections of this chapter have addressed these for specific approaches and responsibilities of the PM.

Most aerospace programs enforce major valuable reviews: system requirements review, mission definition (or conceptual design) review, preliminary design review, critical design review, system integration review, pre-environmental review, and pre-ship review. However, no specific hardware reviews occur between CDR and SIR, yet so much of the cost and schedule risk to a program occurs in this timeframe. This is a clear pitfall in the standard management approach to large and complex aerospace systems. Individual hardware production readiness reviews, and/or fabrication feasibility reviews per subsystem, held informally within each program so as to ensure efficiency, are recommended to maintain attention to the critical developments. Despite the temptation to show a good appearance in front of the customer, additional major customer reviews are strongly discouraged in this time phase because of the dilution of emphasis on solving the hardware needs that arise.

An essential priority of hardware development is to deliver high-quality and fully performing hardware. The aerospace PM must be an active leader during this phase to bring the greatest opportunity for success.

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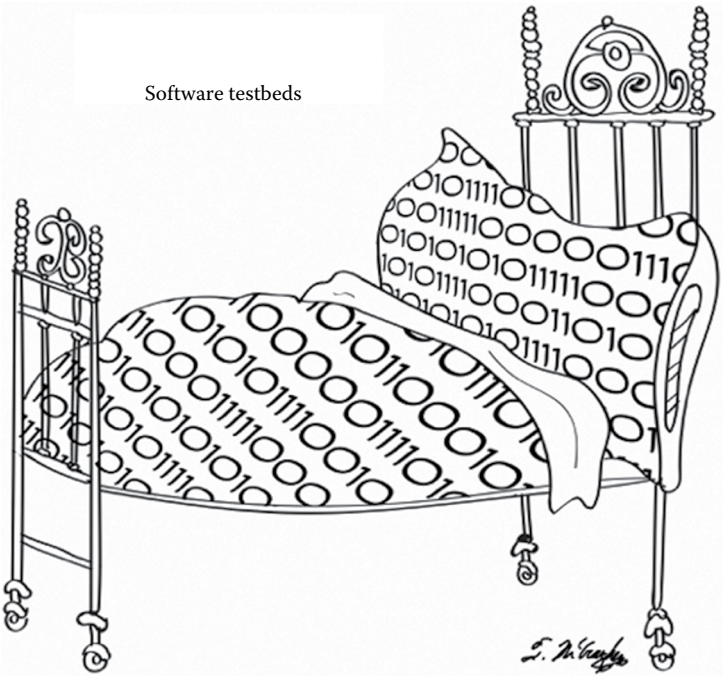
Introduction to Flight Software Systems

Edward J. Birrane III

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Introduction

Any discussion on flight software must start by answering the question "what *are* flight software systems?" The answer to that seemingly simple question can become complicated. Fast. This chapter discusses how to set appropriate boundaries for a flight software system and what things to pay attention to along the way for successful system development.

The most straightforward definition of "flight software" is the complete set of computer instructions running on every processor on the spacecraft. This software is distinct from other mission software running on "the ground," such as software in mission operations centers and science operation centers. However, the definition of flight software becomes nuanced when considering that, from some points of view, a spacecraft is a single entity while, from other points of view, a spacecraft is an aggregation of different components.

The most useful decomposition—from a software point of view—is to divide the spacecraft into two logical components: the spacecraft "bus" (providing common infrastructure for power, commanding, telemetering, etc.) and the set of different spacecraft payloads. Bus software comprises the set of functions necessary for all spacecraft operations—including receiving commands from the ground, sending data back to the ground, booting processors, steering the spacecraft, and storing data to disk. Payload software comprises

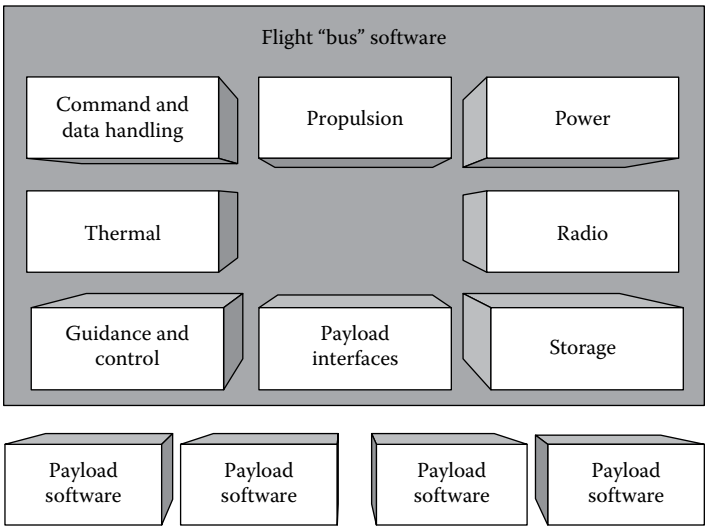


FIGURE 16.1
Bus software controls common capabilities on a spacecraft, separate from the software that controls individual payloads.

the set of functions necessary for the proper upkeep and data collection of the payload itself. Typically, a single organization constructs a software bus, but different organizations build different payloads. This chapter focuses on the set of flight software for the spacecraft bus (Figure 16.1).

Armed with a better understanding of the logical functions covered by flight software, the definition of flight software is concluded by discussing the engineering artifacts produced by a flight software effort. Key artifacts certainly include the set of computer instructions and associated documentation produced by the engineering effort. However, other artifacts include those required to verify and validate the software, such as real-time testbeds, spacecraft component and operating environment emulators, configurations of on-board computational algorithms, and a variety of unit and stress tests to quantify the behavior of the software in relevant operational scenarios. All of these areas are addressed in this chapter and each must be considered a part of the flight software development effort.

Data Race

The distinctions of flight software versus ground and bus software versus payload provide necessary but insufficient architectural guidelines for determining where individual software functions should reside in a space mission. There are times when a software capability could be implemented in flight or on the ground, and this architectural decision depends on unique properties of the mission. For example, deep space missions require more on-board data processing such as compression because of low data rates; near-Earth missions, however, may perform very little on-board data processing because of constant, high-rate, low-latency contact with the ground. Since the decision of what software runs in flight has

significant impact on the number and nature of on-board processors, memory (e.g., random access memory [RAM]), and storage, the decision to allocate a software function to flight must be considered carefully.

A simple architectural design principle to assist in determining what runs where is the principle of the *Data Race*. The purpose of many space missions is the collection, disposition, storage, and transmission of data quickly and efficiently to some ground system; this overarching purpose is referred to at the *Data Race*. If a software capability helps a spacecraft collect, store, and transmit data to the ground more efficiently or in a manner required to meet mission timeliness requirements, then that software should reside in flight. If it doesn't assist the Data Race, it should be implemented on the ground.

The Data Race principle provides an exceptional filter when making architectural decisions on where to place complexity and processing in a space system. Processing critical to the collection and timely retrieval of data to a ground user must be located in the flight system. *Anything else* can be placed on the ground in an operations center with, typically, an order of magnitude less cost and risk in the implementation.

Core Functions

While there are several systems that may comprise flight software, there exist five significant functions of a flight software system (Figure 16.2):

1. Boot
2. Command and data handling (C&DH) systems
3. Guidance, navigation, and control (GNC) systems
4. Autonomy and fault protection systems
5. Communication and radio software

Boot Software

Spacecraft processors need to boot, or initiate software functionality, and will reboot (or restart) for several reasons during a mission. Reboots occur because of software or hardware faults, power load balancing, timeouts associated with extended periods of no

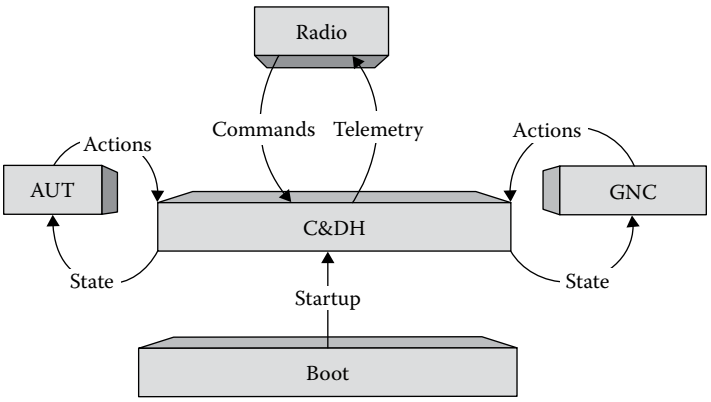


FIGURE 16.2
The C&DH system is the hub of communications in a flight software system.

commanding, and while updating to a new version of software while in flight. In each of these cases, a *bootloader* application must be written to read software images from persistent (i.e., nonvolatile or permanent) storage and load them into memory. Simple bootloaders perform a copy from persistent storage to memory. Complex bootloaders additionally perform checksums and security signatures and produce health telemetry directly to the communications system. It is critical to ensure that the bootloader software for each processor is flawless—since bootloaders are the mechanism for performing software updates, it is difficult (and sometimes impossible) to update them in flight.

Command and Data Handling Software

C&DH software represents the core functionality of a spacecraft system as it handles all commanding into the spacecraft and all data broadcast by the spacecraft as telemetry. Commanding responsibilities include receiving telecommunications protocol units from the communications subsystem, performing protocol processing to extract and verify commands, prioritizing command execution, and running commands while checking for errors. These commands may be destined for the C&DH system itself, or passed through the C&DH to instruments and other subsystems on the spacecraft. Data management responsibilities include collecting health and payload information from all other subsystems on the spacecraft, generating main spacecraft housekeeping and health information, and writing these data to on-board persistent storage. C&DH systems also prepare data for transmission by applying compression and encryption, packaging the data into appropriate protocol units, and passing this information to the communications subsystem for broadcast.

C&DH subsystems are complex in that they must interface with several other subsystems on the spacecraft. Many tasks within a C&DH run continually once per second (i.e., at a 1 Hz rate), with the exception of command management, which may run faster to allow multiple commands to be issued on the spacecraft each second.

Guidance, Navigation, and Control

GNC software governs the self-guided motion of a spacecraft. This software implements a kinematic model of the spacecraft in its environment and uses that model to command the orientation or speed of the spacecraft. The GNC system receives information from the C&DH subsystem such as commands to reconfigure or update the GNC models or provide measurements made by on-board devices such as star trackers, sun sensors, and inertial measurement units. The GNC model outputs a set of commands back to the C&DH subsystem and then out to the thrusters, momentum wheels, torque rods, or other mechanisms used to affect spacecraft motion.

GNC subsystems require significant computational resources. Depending on the mission, these models may run from 1 to 50 times/second (i.e., 1–50 Hz) or more. Separate from the frequency, the nature of the GNC motion models requires significant computational resources due to potentially large volumes of sensor data and multiple, floating point mathematical operations.

Operational and Fault Protection Autonomy Engines

Driven by performance requirements or limits on operator cognitive loading, certain activities on a spacecraft must be automated.

"Operational Autonomy" refers to the automated application of common housekeeping tasks on the spacecraft to reduce operator cognitive load and otherwise limit the chances of human error. These tasks typically involve periodically resetting counters, removing older information from persistent storage, and generating certain telemetry information for transmission. "Fault Protection Autonomy" refers to situations where the spacecraft itself must make a commanding decision, without operator oversite, to react to a hardware or software failure or other critical system event.

These systems are typically modeled using a monitor-response paradigm where a set of monitoring predicates are given to a configurable evaluation engine and associated with a set of predefined command reactions. The popularity of this approach is that it provides a *deterministic* response to events which is critical to the forensic analysis of spacecraft state when recovering from an anomaly (or when trying to perform recovery of a nonresponsive system).

Autonomy engines represent a unique engineering approach to altering the behavior of spacecraft in flight without altering flight software. As spacecraft age, the conditions that must be monitored also change, and the desired responses to those conditions change. Rather than hardcoding behaviors and requiring a flight software upload (and reboot) each time a change must be made, autonomy engines treat monitors and response conditions as a configuration parameter.

Telecommunications Software

Telecommunications systems implement the multiple communications protocols necessary for the proper wireless data exchange. In this respect, spacecraft telecommunications systems are similar to terrestrial systems, such as the Internet. In terrestrial systems, multiple protocols (Ethernet, IP, TCP) are layered, with each layer responsible for some aspect of data exchange. For space systems, the Consultative Committee for Space Data Systems (CCSDS) defines international protocol standards in much the same way that the Internet Engineering Task Force (IETF) defines standards for terrestrial networking. The CCSDS is a common, but not universally required, standard for space system telecommunications.

Support Functions

In addition to the construction of flight software, there are three main supporting features kept within the flight software work breakdown structure (WBS): testbeds, autonomy, and acceptance testing.

Testbeds

Testbeds refer to the racks of equipment providing software simulations and hardware emulations of critical spacecraft components so that flight software may be adequately tested before installation on the spacecraft. There are multiple stakeholders for testbed development, including flight software developers testing software; autonomy engineers analyzing the responses of flight software to fault events; ground software engineers testing interfaces; spacecraft testers and integrators developing policies and

procedures; hardware developers evaluating the performance of breadboard, engineering, and flight versions of components; and mission operators testing command sequences prior to uploading them to the spacecraft. Typically testbed teams range in size from two to four developers depending on the complexity of the testbed components. Large missions may commission anywhere from 9 to 12 testbeds based on the expected number of concurrent users over the course of mission development.

Autonomy

Autonomy refers to the implementation of fault protection and operational automation on the spacecraft as a function of the capabilities of the autonomy engine included in the flight software system. The autonomy team generates autonomy configurations as an activity separate from the flight software engineering effort. For example, fault management systems engineers on a spacecraft will determine fault conditions and necessary mitigations and flow requirements and constraints to the autonomy team. In doing so, the autonomy team will review the flight software system design, determine what data is available for the system to recognize fault events, and what commands are available to implement, in flight, required mitigations. In performing this function, autonomy will levy requirements and constraints on the flight software system to collect individual data and execute certain commands. When properly executed, this approach provides an integrated software solution developed by teams with distinct responsibilities working in tandem with a series of checks and balances.

Acceptance Testing

Acceptance testing verifies that individual flight software releases meet critical requirements and perform as expected on the testbeds. This level of testing requires a working relationship with the flight software engineering team and the testbed team and serves as a gating function to other testing activities that have less interaction with the engineering teams. The size of the acceptance test team varies by the scale of the project but typically comprises three to five test engineers for large missions.

Structuring the Software Effort

As described, the flight software systems cover a dynamic range of software disciplines that must be managed under a single effort. This subsection includes the organization breakdown structure (OBS) of a typical software effort and common software development milestones.

Flight Software OBS

Figure 16.3 outlines a typical organizational breakdown structure for a spacecraft flight software system. This OBS is segmented into three major areas: software systems engineering, software technical leadership, and software support.

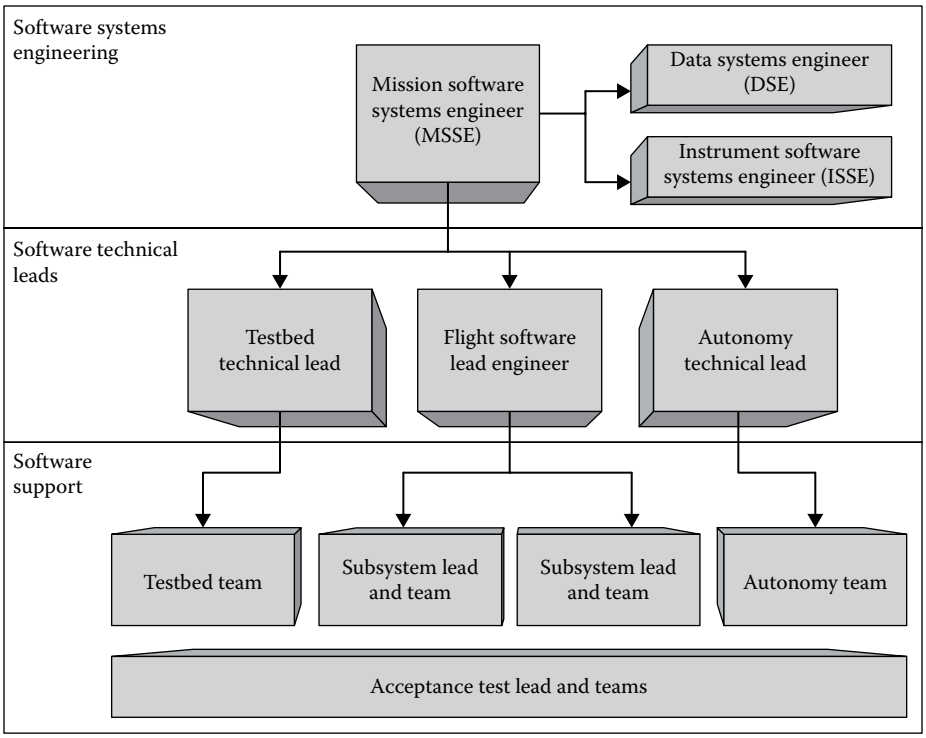


FIGURE 16.3
A flight software team consists of systems engineering, technical leadership, and multidisciplinary engineering teams.

Software Systems Engineering

Flight software interfaces with many of the physical subsystems on a spacecraft. Therefore, understanding how data and control information flows across these subsystems is required to design and implement software components. This analysis is termed *Software Systems Engineering*. Three types of software-related systems engineering functions can be allocated to the software team: the *Mission Software Systems Engineer* (MSSE), the *Data Systems Engineer* (DSE), and the *Instrument Software Systems Engineer* (ISSE).

Mission Software Systems Engineer: The MSSE acts as the coordinator for all software in the mission, including flight software and ground software. However, since spacecraft have many more resource constraints than ground stations, the MSSE typically focuses on capturing what system function must be implemented in flight and what services can be moved to ground software. In essence, the MSSE applies the Data Race filter to allocate software functionality to the appropriate system segment (e.g., flight or ground). This includes developing technical concepts for flight software based on mission and spacecraft requirements and using any constraints levied by the proposal manager and system engineer.

Data Systems Engineer: The DSE oversees the end-to-end data flows for the mission. End-to-end, in this context, refers to the collection of data on-board the spacecraft by payloads to the ultimate delivery of those data at appropriate payload or mission

operations centers on the ground. Principal components between these endpoints include flight systems (solid-state storage, C&DH, telecommunications) and ground systems (space networks and mission operations centers). The DSE calculates the overall data budgets for the mission, to include needs for secondary storage, data rates, timeliness requirements, and pass durations. The DSE accepts mission and spacecraft constraints on the nature, duration, and speed of contacts with the spacecraft and levies constraints on payloads as to how much data can be produced. The DSE also works with payloads to determine whether functions such as data compression are handled individually by payloads or centralized in the C&DH.

Instrument Software Systems Engineer: The ISSE coordinates the implementation of flight software across the organizations providing individual payloads for the spacecraft. This includes coordinating the software development plans, technical reviews, interface control documents, and other engineering artifacts to ensure that all payloads are built with similar quality processes and to converging delivery schedules.

Software Technical Leads

Technical leads guide the day-to-day technical management of the flight software and related implementations. These roles include the flight software lead, testbed lead, autonomy lead, and flight software subsystem leads as necessary for the project.

Autonomy Technical Lead (ATL)

The ATL leads the development of the autonomy system for the spacecraft. An ATL separate from the flight software lead (FSL) should be considered in missions where sophisticated autonomy is required—such as cases where there exist redundant hardware components and perturbations of science or operational timelines as part of autonomy responses. The ATL interfaces directly with fault protection systems engineers who determine likely failure cases for the spacecraft. The ATL levies functional and performance requirements on the FSL. In cases where the on-board autonomy system is engine driven, the autonomy team is separate from the flight software team and develops autonomy configurations rather than flight software. The ATL also coordinates testing for all autonomy responses on the spacecraft independent of flight software testing.

Flight Software Lead

The FSL leads the flight software engineering team and coordinates with software systems engineers. The FSL produces the following artifacts for the mission:

- A tracked flight software schedule synchronized with the mission program
- A staffing profile and staffing assignments coordinated with line management
- Software development plans to define the flight software effort
- Flight software system requirements, coordinated with the MSSE, DSE, and ISSE
- Architectural and detailed design artifacts for mission Preliminary Design Review (PDR) and Critical Design Review (CDR)
- The allocation of requirements to staged, scheduled software builds
- Technical reviews of flight critical software and other components as deemed necessary

- Released documentation per software build, including new features, fixed issues, unit testing artifacts, user's manuals, and other training materials
- Software quality assurance metrics during development and post-development

Testbed Technical Lead (TTL)

The TTL leads the testbed software team and coordinates with software system engineers and other spacecraft component engineers as necessary to build test harnesses to evaluate the performance of flight software and verify its function against system requirements. Similar to the FSL, the TTL produces the following artifacts:

- A testbed software schedule synchronized with the mission, hardware, and software schedules
- A testbed software development plan and software requirements specification
- Testbed Preliminary and Critical Design Review design materials, including interface control documents
- For critical testbed software, an acceptance test plan and acceptance test specification
- For each software release, release notes and a user's guide

Software Support

Software support includes the technical teams performing engineering support at the direction of their technical leads. Additionally, this area captures the acceptance test effort and any additional hierarchy associated with the flight software engineering effort.

Acceptance Test Lead

The acceptance test lead oversees efforts by the flight software WBS to verify that a particular release of software appropriately performs its function. The lead and team produce the following artifacts:

- A testing schedule coordinated with the flight software schedule
- Test scripts, policies, and procedures to demonstrate the functional requirements of flight software and to verify expected results
- Acceptance test plans, test specifications, and test results

Flight Subsystem Leads

Each functional area of a flight software system may have a dedicated technical lead based on its size and complexity. For very large programs, one subsystem lead per critical software function may be allocated to the program. For very small programs, a single subsystem lead may oversee multiple functional areas. A common metric for determining the effective number of subsystem leads is to estimate the complexity of each functional area, calculate a staff count to each area based on its complexity, and then allocate subsystem leads to ensure that no lead oversees more than six to eight staff.* Table 16.1 summarizes potential technical leadership staffing for large, medium, and small projects.

* The engineer-to-lead ratio is typically very small for embedded, real-time systems to account for the increased complexity of this type of software. Additionally, spacecraft hardware and operating systems rarely provide the kind of protections found in modern terrestrial operating systems increasing the cognitive load on both engineers and technical leads.

TABLE 16.1

Allocation of Subsystem Teams Is Driven by the Overall Size and Complexity of a Mission

	Small	Medium	Large
Overall	FSW lead	FSW lead	FSW lead
Boot	SSL 1	SSL 1	SSL 1
C&DH	SSL 1	SSL 1	SSL 1
GNC	SSL 1	FSW lead	SSL 2
Autonomy	SSL 1	SSL 2	SSL 3
Radio	FSW lead	FSW lead	SSL 4

Software Development Activities and Milestones

This section outlines key process activities and milestones associated with the flight software effort. Activities and milestones for testbeds, autonomy, and acceptance testing follow the same process as flight software and should be custom-tailored for each mission using flight software as a guide. Figure 16.4 lists critical flight software process activities and recommended products and reviews as a function of process activity.

Figure 16.4 implies a logical and linear progression of process activity across a flight development effort. However, this simply captures the dependencies between logical steps in the development effort. It is highly recommended that flight software be developed, tested, and released as a series of builds adhering to some incremental build strategy. The following is a recommended build schedule for flight software tests:

- Build 0: Toolchain, commercial-off-the-shelf (COTS), constraints
- Build 1: Simple commanding
- Build 2: Complex commanding, some GNC, Boot
- Build 3: Full System Suite
- Build 4: Bugs fixes, prelaunch
- Build 5+: Point releases for bug fixes and enhancements, including postlaunch builds

Reviews

It is recommended that the MSSE for the spacecraft be involved in all reviews, starting with the Mission Concept Review (MCR) and persisting through to Flight Readiness Review (FRR). However, software artifacts are only generated for a smaller subset of the spacecraft development, typically starting with the Software Requirements Review (SRR) and ending with the System Acceptance Review (SAR). For each of these reviews, a software-specific review is held before or after the actual program review, with the program-level review reserved for the summary of the software-specific review or to provide guidance for the software-specific review. Software-specific reviews allows for a more technical audience and targeting discussion of software systems than can otherwise be accommodated in a program-level review.

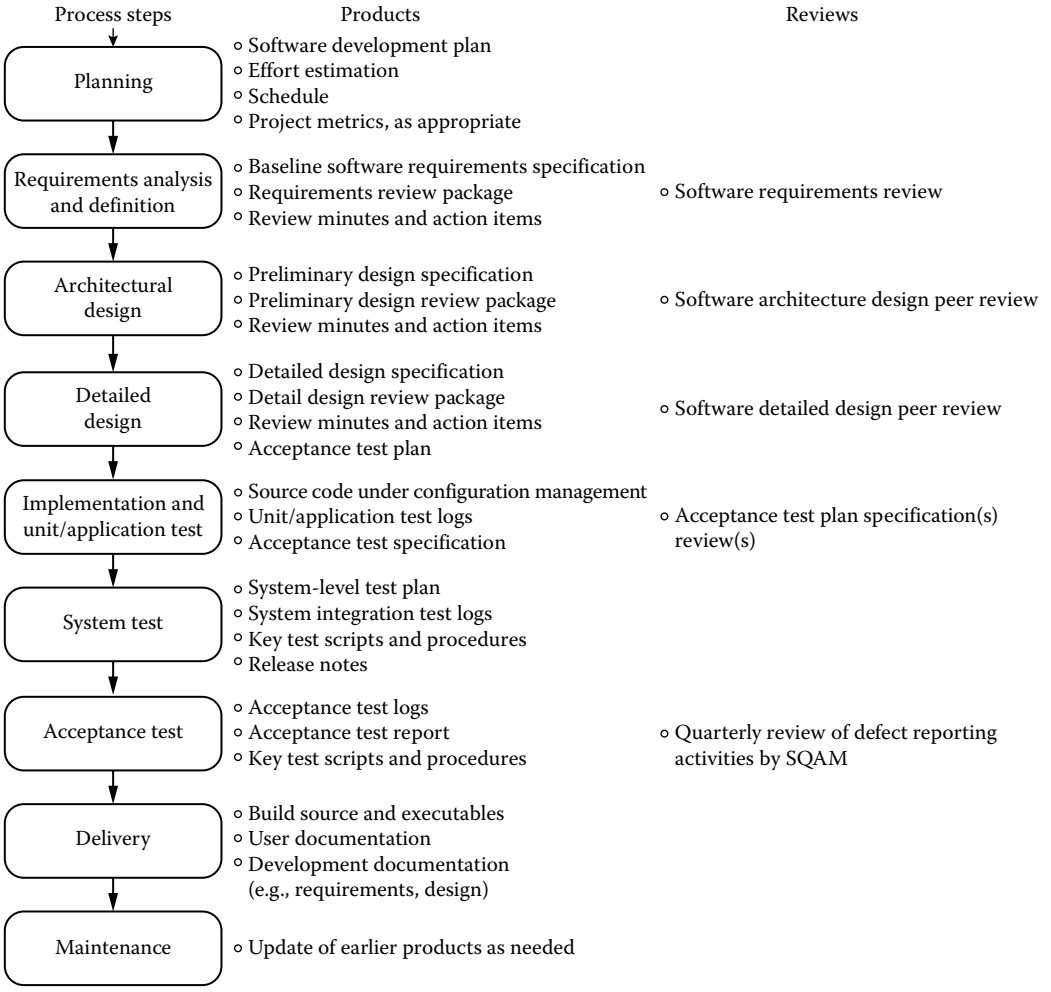


FIGURE 16.4
Key milestones along the flight software development lifecycle generate specific artifacts and associated artifact reviews.

Software Requirements Review

This review typically lags system and mission requirements activities, as software requirements are derived from higher-order requirement specifications. Since software requirements are directly traced to software design and testing activities they must be critically evaluated for their specificity, measurability, and realism.

Software Architecture Design Peer Review

A software "architecture design review" typically focuses on the architectural components of the flight software system and occurs around the time of the mission PDR. The following are examples of artifacts that effectively capture the information for this review:

- Task communication graphs
- Major architectural components

- Context diagrams
- Definition of data interfaces including definition of ICDs needed
- Enumeration of critical performance measurements
- The notional timing graphs for critical performance areas

Software Detailed Design Peer Review

A software "detailed design review" focuses on the individual components that will comprise the flight software and occurs around the time of the mission CDR. The following are examples of artifacts that effectively capture the information for this review:

- Modules and critical application programming interfaces (APIs)
- ICDs
- Prototype results where necessary for critical performance reviews
- Updated timing graphs
- In task communication graphs
- Flowcharts through select logical areas

Acceptance Test Plan/Specification(s) Review(s)

An "acceptance test plan/specification review" focuses on the procedures, data, and methods used to verify the functionality provided by individual software builds. A multibuild system is recommended for flight software systems to allow the iterative and incremental release of functionality.

Quarterly Reporting of Defect Reporting Activities

A Software Quality Assurance Manager (SQAM) should periodically evaluate quality metrics as generated by the flight software team. This review will directly influence the development activities and schedules associated with the flight software effort.

Common Technical Challenges: What Can Go Wrong?

Software technical challenges are specific to the mission, environment, and hardware. However, there exist categories of likely challenges that can be addressed with the proper allocation of resources as a function of program management.

Resource-Based Challenges

Spacecraft are rarely over resourced. As additional computation/storage capabilities increase, overall system size, weight, and power traditionally increase, which, in turn, increase cost, schedule, and risk to the mission. The avionics packages used to run software are constrained by processing power, nonvolatile storage, and volatile storage. Each of these resources MUST be tracked and reported at critical points in the software lifecycle.

TABLE 16.2

Amount of Margin Considered Healthy for Flight Computers Changes over the Course of the Mission

Margin	Description	At PDR	At CDR	Launch
CPU	The % of idle time on processor during worst-case loading averaged over a unit time (e.g., 1 Hz)	>50%	>40%	>20%
Data storage	The % of writable non-volatile data (flash or EEPROM) available after worst-case data usage.	>50%	>35%	>10%
	The % of non-writable data (PROM) available after worst-case data usage.	>40%	>10%	>10%
RAM	The available working memory associated with each processor under worst-case conditions.	>50%	>35%	>10%

The standard way of reporting this information is to measure the percentage of the resource as utilized by the software averaged over some unit of time while operating under relevant mission-like conditions. This percentage is expressed as the *margin* available for this particular resource. The purpose of reserving margin for resources is to account for additional software development, bug fixes, or enhancements that may be encountered during the life of the mission. It is typical to require significant margin early in a software development effort and then relax the required margin through multiple software builds as the spacecraft nears launch. Common resource margins, their descriptions, and guidance on minimum requirements are shown in Table 16.2.

The frequent calculation of resource margins throughout the software effort should be performed by the MSSE and incorporated into spacecraft risk management processes at regular intervals. It is very important to measure resource utilization with realistic, representative functionality for real mission conditions, which must be estimated early in development and updated as understanding evolves; a potential risk is that software resource utilization margins are low, however test/estimation functionality that is not mission realistic hides this situation until late in development when it is much more costly to address.

Timing Analysis

In seeking an optimal balance between software capability and hardware resources, there will be times when the software exceeds its margins and analysis must be performed to understand the impact of this situation.

Software developers MUST have ready access to the types of tools that allow appropriate profiling of software execution on flight processors.

Hardware Issues

The toolchains used by software engineers for development using desktop computers provide rich debugging and profiling capabilities at little to no cost. However, the flight software runtime environment consists of embedded, real-time operating systems running on custom hardware. When software migrates from the development environment to the runtime environment, it will exhibit different performance. Tools, cost, and schedule must be allocated to account for the transition of software from the desktop environment to the flight-like hardware environment.

Profiling and Debugging Tools: A significant cost of a real-time operating system is the set of profiling tools provided for use by developers. Expensive systems such as the VxWorks Operating System by WindRiver provide excellent tools to track down issues when transitioning to flight hardware. However, the price of these tools for the development team may be prohibitive for smaller missions. Open-source, real-time operating systems such as RTEMS are free for use and provide some profiling and debugging tools, but often require significant developer time and specialized expertise to track down complex logic and timing errors. Programs must recognize that the costs saved by using less capable (but less expensive) tools may be offset by an increase in labor. As such, a trade must be done on the total costs associated with a particular toolchain early in the mission; changing tools once development has begun can be extremely difficult.

Logical Probes: Even when spacecraft systems select community or commercial operating systems and processors, they may be embedded within custom-built computer cards or interface with custom-programmed field programmable gate arrays (FPGAs). When missions design their cards or FPGAs, the software team *must* be involved in the design of these components to ensure that they support the types of logical tracing compatible with the architecture of the software system and the toolchains to be used on the mission.

Cost Drivers

Unexpected costs become technical challenges when functionality, staffing, or other tradeoffs must be made to keep the software development effort within appropriate cost and schedule margins. There are several common technical approaches to building software systems that can reduce the likelihood of increasing costs in a software effort.

WBS Tracking: Where possible, a separate flight software WBS item should be used to track the integration into, and debugging of, hardware interfaces for software systems. This includes working with hardware development teams to design logic interfaces, testing those interfaces, and helping forensically track system errors to either hardware or software implementation.

Compute Engines: Where possible, tasks in a flight system should be built as configurable engines separating the implementation of the engine from the conditions and responses evaluated by that engine. A typical example of such an engine is fault-protection autonomy, where a monitor-response engine may be codified in flight software, but autonomy predicates can be configured at any time. Telemetry systems are also candidates for engine-driven development, where a telemetry engine can be configured at runtime with telemetry page definitions. The benefit of engines is that changing a configuration does not require changing flight software itself, which would incur significant design, implementation, and test costs as well as risk to the spacecraft to apply a new flight software upload.

Spacecraft Interfaces: Several aspects of flight software can be reused across missions, particularly in the area of C&DH, including command ingest, data collection and storage, and telemetry generation. The most significant cost drivers for flight systems involve changes to the spacecraft hardware itself, which is typically driven by mission performance requirements. For example, boot systems must be updated when changing processors, operating systems, and avionics board components.

GNC systems are custom-built to the kinematics of the spacecraft and its specified sensors (star trackers, sun sensors, etc.) and actuators (momentum wheels, thrusters, torque rods, etc.). These components must be set early in the mission as changes to these elements, their interfaces, or the types of data they produce will have *significant* impact on the cost of interfacing software.

Software Testing

The staff, tools, and engineering required to verify the proper operation of flight software can cost as much, or more, than the actual development of the software. As a necessary part of creating appropriate software, planning the software testing effort must be given the same consideration as the software engineering effort itself.

Types of Testbeds

Software-In-The-Loop: Before engineering models and flight-like hardware become available, software simulators for avionics components, instruments, and the environment can be assembled to support early testing of commands, telemetry, and on-board processing algorithms. It is important that the early software builds (Build 0, Build 1) can test in the most flight-like environment possible to minimize the likelihood of having to refactor software later in the mission when hardware components are installed.

Hardware-In-The-Loop: As engineering units and flight hardware are constructed, they are installed into testbeds to start placing hardware in the testing loop. Hardware can replace software simulation where appropriate, allowing the testbed to evolve gracefully in pieces over the course of the mission. Eventually, some testbeds will be entirely populated with flight hardware and will transition to a full hardware-in-the-loop testbed serving as a ground-based truth model of the flying spacecraft.

Types of Testing

Acceptance Testing: Acceptance test activities verify that a particular release of software fulfills its system purpose. This is more general than the unit tests performed by flight software engineers and more particular that the types of independent verification and validation tests performed as part of program milestones. Additionally, the acceptance test activity should consider stress tests to quantify the behavior of the software system when driven past its requirements. This type of testing typically requires acceptance test engineers to work with flight software engineers to ensure a proper understanding of the internals of the software system. However, flight software engineers should not fill the roles of test engineers. In cases where there must be an overlap, a flight software engineer must not test their own software. As a flight software centered activity, the acceptance test team should be kept under the flight software WBS.

Scenario Testing: Scenario tests are contrived by subject matter experts to describe specific operational situations of critical important to the mission. Often, these tests exercise particular combinations and dependencies amongst and between requirements in ways that are not always covered by acceptance tests. For example, scenario tests may recreate particular data collection events or mission simulations to characterize the performance of the software (and hardware) system. Scenario tests are particularly useful for discovering occurrences where performance requirements do not completely capture the necessary behavior of the system.

Stress Testing: Stress tests differ from other types of tests because they do not seek to verify the proper operation of the system. Rather, stress tests drive the software system to failure to observe *how* the software fails in a variety of stressing scenarios. Understanding how software fails is invaluable in determining the risks associated with the spacecraft being left in an unanticipated condition, such as during a hardware failure, a misconfiguration from user error, or some other in-flight event.

Wrap Up

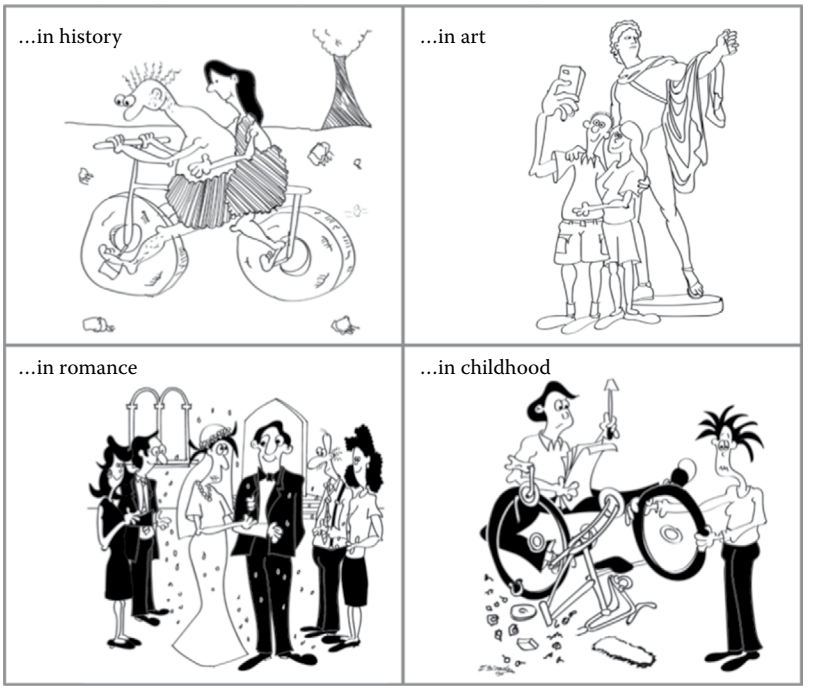
Flight software consists of the logical functions implemented in software running on spacecraft computers in either the spacecraft bus or in spacecraft payloads. Flight software, additionally, includes the set of activities necessary for the verification and validation of that software, to include the construction of necessary testbeds. The cost and complexity of flight software is contained by careful architectural evaluation of what software runs where in a mission. Wherever possible, mission software functions should be located on the ground, and the principle of the Data Race must justify capabilities required in flight. The staffing of a flight software system includes system perspectives (MSSE, DSE, and ISSE), technical leadership (ATL, FSL, and TTL), engineering teams, and acceptance testing teams. Together, these teams produce artifacts for various software builds across multiple program milestones, with software-specific reviews either leading or lagging mission-wide reviews. The bulk of challenges associated with flight software development stem from lack of computing resources in flight computers, the availability of profiling and debugging tools, and the maturation cycle of custom-built spacecraft hardware. Ultimately, the proper verification and validation of flight software requires software- and hardware-based testbeds and multiple testing approaches, including acceptance, scenario, and stress testing.


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Section IV

Aerospace Project Management Special Topics

Project Management—Phase C/D (Design and Development) Reviews:
Preliminary Design, Critical Design, Test Readiness, and Flight Readiness Reviews




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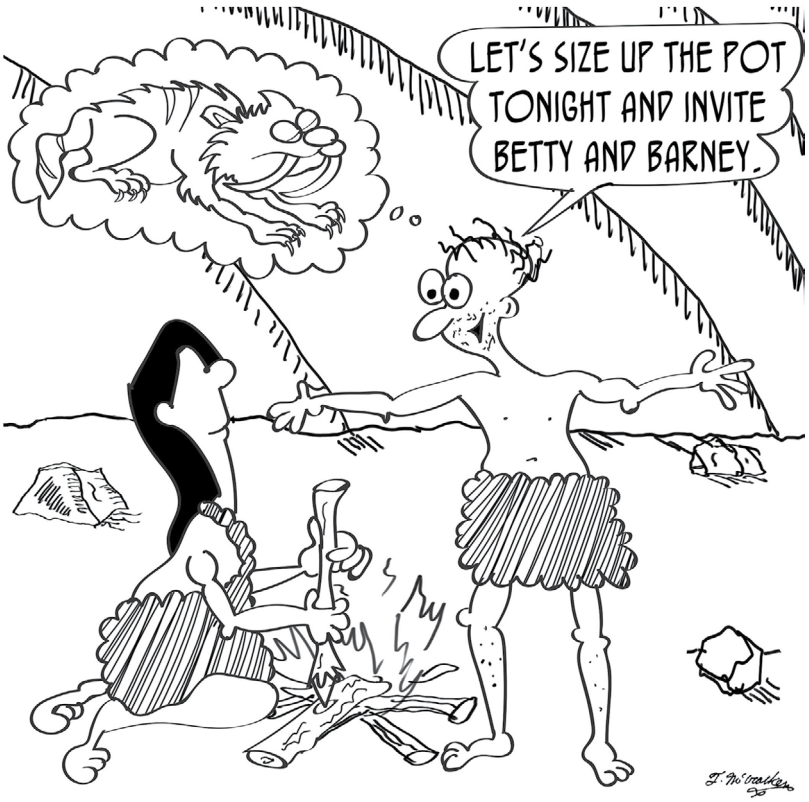
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Communicate! Communicate! Communicate!

Richard J. Fitzgerald

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IDENTIFY AND COMMUNICATE
WITH PROJECT STAKEHOLDERS



WEEKLY AND MONTHLY STATUS REPORTS ARE IMPORTANT IN KEEPING PROJECT STAKEHOLDERS PROPERLY INFORMED

Fundamentals of Communication

Communication is a fundamental part of human existence. People need to impart information to each other, to achieve goals, cause the desired response, or just share an idea. Broken down to fundamental terms, the act of communicating is only transporting information from one person's brain to another's. Humans have a natural desire to understand who, what, where, when, why, and how. Transporting information satiates the desire of the possessor to transmit and the recipient to receive. These human traits form the basis for multibillion dollar per year industries to provide tools and methods for people to communicate with each other. In today's society, communication takes place across more media types than ever before. Social media tools can provide instant information to people across the world. More and more types of social media are being adopted in the workplace, as businesses and governments adapt to changing methods and norms of communicating within and outside their organizations. Today's smartphones, for example, are functionally more powerful than supercomputers were 30 years ago. The Cray-2 supercomputer of the mid-1980s ran at 1.9 G Floating Point Instructions Per Second (G FLOPS) with a CPU speed of 244 MHz, while the Apple iPhone 4 runs at 1.6 G FLOPS with a CPU speed of 800 MHz [1]. Today's tools such as video conferencing, desktop conferencing, and file sharing of technical data make exchanges of information quicker and more efficient than even recent versions of the same tools. This increase in communication power can be very useful, if used correctly.

In a space flight project development environment, these types of communication tools have become commonplace. More and more information is being dispersed at higher and higher rates. One would expect that with such an increase in communication methods, information exchange on flight projects would be more efficient, and miscommunication errors would be virtually nonexistent. While the volume of information exchange has increased, miscommunication still exists. Why is this? Fundamentally, the amount of information and the speed at which it is delivered are immaterial, if the information is not accurate or if necessary stakeholders are missing from the receiving side. Many flight projects remain susceptible to cost and schedule overruns, as well as technical problems [2]. Fundamentally, many of these issues can be traced back to miscommunication. Even technically successful projects have problems along the way. Increased communication is often the reason they get healthy again. A conscientious team effort to communicate clearly to all those who need to know is one of the most powerful building blocks for project and mission success.

In a space flight project development environment, lack of communication can lead to bad results. Programmatically, poor communication can result in schedule delays, cost overruns, and incorrect reporting in both areas. Project teams that do not communicate clearly among each other and to their sponsors can be relying upon faulty programmatic data, which in turn means unexpected overruns late in the development cycle. This is the worst possible time to discover an overrun, especially if up to that point all metrics governing programmatic health looked fine. How can this happen? It is rarely intentional. Cost and schedule reporting errors can crop up, due to lack of communication of their status within the team and to the sponsor.

An example of poor programmatic communication would be delays in the development of a spacecraft subsystem, due to parts and materials procurement problems. If the subsystem engineer does not notify the spacecraft manager and the project manager of these delays, the ability to replan around the problem at the next higher level of assembly is limited. The subsystem engineer may decide not to lien or threaten the subsystem schedule margin and delivery date to the spacecraft for observatory integration and test. Perhaps this is due to the optimism that once the parts and materials arrive, the schedule might be accelerated and the delivery date kept. Everyone wants to meet their commitments, so the engineer's intentions are good. The problem with this is that the project manager is now unaware of a potential schedule hit to the overall project schedule, especially if this subsystem is already on the critical path. If the optimistic schedule kept by the subsystem engineer does not materialize, the result will be a delay on the critical path, which surprises everyone and creates bad feelings within the rest of the team and with the sponsor. Better recognition of this problem, communication to the entire team, and proper planning to allow for this risk would help avoid a sudden bad surprise.

An example of poor technical communication might be a science instrument provider with a technology development problem. There is often time a technology development associated with science instruments, as they tend to be "cutting edge" elements of the space flight mission. Should the technology development not proceed on the budget or schedule set up at the beginning of the project, careful replanning would take place to accommodate difficulties. Problems are compounded if the instrument science team does not share the problems being encountered with the rest of the team. If the science instrument development team decides to add resources to develop several alternative

technologies or just add resources to debug the planned technology without informing the project manager, costs can run well above the plan quickly. This kind of surprise is unwelcome and will likely lead to an overall overrun by the time the instrument delivers to the spacecraft.

Poor communication can also occur at the mission level. Missions have many stakeholders, all of which need appropriate and frequent information, to effectively support the effort. The project team, institutional management, and sponsor need timely and accurate technical and programmatic information to carry out their respective functions effectively. When this information is not communicated clearly, accurately, and frequently, problems can arise. An example might be miscommunication between a project office and its sponsoring program office. Technical development issues and associated programmatic impacts need to be openly and clearly communicated from the project to the program each month. Sometimes projects become too heavily involved in the problem to pause for accurate assessment and reporting. When this translates into data lag or purposeful suspension of reporting, the sponsoring program office becomes ineffective in assisting or correcting the course of the project office. Concrete examples of this type of communication gap exist in the space flight industry. In one specific instance, prolonged periods of inaccurate and incomplete reporting from the project office to the program led to a 2-year launch delay. The program office was forced to make decisions based on incomplete information and the project office resisted reporting details until it felt its problems were fully addressed internally. That decision cost the project precious time and budget, ultimately leading to a significant launch delay. The root of the delay was a lack of communication and a poor relationship between the program and project office. A relationship based on trust and open communication could have avoided this undesirable outcome.

What does good communication look like? How can it save time, money, and solve technical problems? Effective project communication takes the form of e-mails, team meetings, programmatic reports, status presentations, and even social events. Let's take two of the examples of poor communication mentioned earlier. In the first example, the subsystem lead felt as though the solution to procurement delays was within his/her control. While that may be true, communicating these problems to the spacecraft engineer and project manager could have resulted in acceleration of these procurements. Suppose the spacecraft engineer knows of other projects with the same parts on the shelf that they may be willing to give up in exchange for the new parts when they arrive. Perhaps the project manager knows someone at one of the vendors from previous programs and can make a call to get higher priority. These possible outcomes are never realized if the information is not promptly communicated to all the stakeholders. If nothing else, the spacecraft engineer and project manager could develop schedule work-arounds in advance of a late subsystem delivery. Options remain open if notification is given in the proper timeframe.

In another example mentioned earlier, the instrument science team could potentially benefit from additional resources in the form of people, facilities, or materials, if they had notified the project manager soon enough. Resources to help solve technical problems may exist elsewhere in the project team or at other institutions. The sooner the problems are identified to all the stakeholders, the sooner such resources can be applied. As a minimum, stakeholders are at least aware of the situation and not surprised if the instrument delivers late or cannot meet all technical requirements. The end goal is for the entire mission to be successful, not just any one element. When project teams think in those terms, communication may flow more freely.

Project Stakeholders

The term stakeholder has frequently been used, but who are the project stakeholders and how does any given team identify them? A stakeholder is any person or organization that has an interest in the outcome of the project. In a typical flight project, the list of stakeholders may include the project team, the sponsor organization, the project team's senior management, partnering organizations and their senior management, vendors, launch vehicle provider, the science community, and the public. Each team may have a slightly different set of stakeholders. To identify stakeholders for a team, some questions might be used in this process. Who is funding the project? Who is administering the project? Who will produce data from the project? Who will use the data from the project? Who is building the spacecraft and instruments? Who is launching the mission? Who is operating the mission? Whose reputation is at stake? The answers to these questions help the team understand who needs information along the way. This is not to mean all stakeholders need the same amount of information at the same level of detail at the same time. Quite the contrary is true. The launch vehicle provider, for example, does not need to know low-level details of troubles with the avionics development on the spacecraft. They do need to know if the observatory delivery date is at risk, however. Sponsors need to know when risks and problems arise. They will usually determine what level of detail they expect in reporting to them. How and when you communicate to stakeholders is crucial.

Methods and Practices for Effective Project Communication

Effective communication within the project team is the cornerstone of a good project. Project communication should be a mix of regular meetings and e-mails on a predictable cadence. Typically, there are several levels of this kind of communication. Beginning with the small group of team members who lead the team, a weekly face-to-face meeting with the project manager is appropriate. This "core team" usually consists of the project manager, the deputy project manager(s), financial or business manager, mission system engineer, spacecraft engineer, instrument system engineer(s), science lead or principal investigator and leads for specialty areas such as integration and test, and mission operations. Membership can vary project to project. The sponsor is not usually part of this meeting.

The purpose of the weekly core team meeting is to get everyone up to speed on project risks, issues, and concerns, as well as efforts being undertaken to address them. The project manager should come prepared with an agenda sent out before each meeting. The agenda should cover all current topics, with an opportunity for the walk on items from each person. Each member should feel empowered to discuss problems and contribute ideas for improvement, without negative consequences. The meeting should have a "collaborative" tone to it. Feeling part of a high-powered team that is dedicated to identifying and solving problems is important and empowering to its members. This holds true for all project members.

Project news and status should also be communicated from the project manager across the whole project team on a frequent basis. This can take the form of a meeting, videocon, or telecon. A periodic project status e-mail is also helpful. Project team members feel more

connected to the project when they have an opportunity to participate in team meetings and receive news directly from the project manager. Another helpful project wide communication tool is a project website. Project news and information can be posted for viewing at team member's leisure. Information such as presentation material, development status, science overview, team member profiles, launch date countdown, team member contact information, photos, and organization charts can be placed on the website. Additionally, password protected file sharing areas can be set up for an exchange of sensitive project files and other information.

As a general topic of communication, project norms should be established for use of e-mail. These should include common practices such as honoring the "chain of command" by adding personnel in the CC list of an e-mail who are intermediate in the management chain between the sender and the recipient. Also, it is good practice to include personnel in the CC list who are named in the body of the e-mail. Sensitive information would be an exception to this convention. Responders to e-mail should be thoughtful of the "reply all" button and only use it if everyone should be aware of the response. Like all communication, e-mail CC lists should include stakeholders appropriate to the level of information being transmitted. That is a subjective decision, but when the sender takes the time to simply consider this, communication is likely to become more effective.

Communication external to the project is also important. Projects typically produce a weekly written summary report, covering ongoing activities, status, and accomplishments. The target audience is usually the sponsor and senior management, but can be shared across the team. The accuracy and reliability of this report are critical to keeping stakeholders up to speed on a regular basis about project happenings. This is the best way to communicate late-breaking news, as monthly status reports are sometimes stale or dated.

Finally, every project should have a written emergency communication plan in place. This means types of emergencies are defined and contact lists preestablished. Situations such as accidents with flight hardware, personnel injury, severe weather threats, and accident recovery should be communicated quickly, accurately, and to the right stakeholders. Senior management and sponsors should be contacted immediately, then other stakeholders soon after that. The project's emergency communication plan should have a "phone tree" of people to be contacted, including their e-mail and cell phone numbers. There should also be the definition of specific time requirements for communicating certain types of accidents or events. Codifying and releasing such a plan early in the project life cycle is important so that all stakeholders understand the process. Having a written plan to follow is critically important when such events occur, as this prescribes the steps to be taken. The responder then does not need to think about the process, but rather focus on the problem and corrective action.

Public Communication

Public communication may or may not be applicable for flight projects. Flight projects in civil space must certainly plan for such communication, while flight projects in the private sector or for defense-related applications may not. For projects that do need to communicate with the public, most organizations have experts on staff to assist with communicating with the press and other media. Project teams should take advantage of this expertise to

communicate appropriately and effectively with the public. Publishing articles in magazines or professional journals usually involve a vetting process within an organization, before external release. Each organization will have a process or procedure for completing this task. Project managers must be aware and comply with these processes. Additionally, project team contact with the media is best coordinated with the organization's media professional first. Television, radio, newspaper, and website interviews can be tools for promoting a flight project, if properly organized. Media professionals can prepare project team members for expected questions, pitfalls of answering certain questions, and establishing proper project messaging. Project teams should take advantage of this assistance before interviews. Media professionals can also be a part of the project team, when dealing with website content, showcase events, social media outlets, and other types of public communication and outreach activities. When properly planned, these communication tools can provide meaningful information to the public, which enhances the image and interest of the project. If improperly planned or executed, the reputation of the project, home organization, or individual people can be severely damaged. Mistakes such as inappropriate or derogatory comments, incorrect information, or misquoted references can cause major impacts to people and organizations. Proper preparation can avoid these mistakes.

Project Communication Content

Some of the most important information to be communicated during the project life cycle involves technical and programmatic status to sponsors and internal organization senior management. Keeping the sponsors and management informed and engaged during the project development process is good for them, as well as the project team. This is especially important when problems, issues, and concerns arise (as they always do) during the development cycle. Providing timely information about problems and reporting on corresponding corrective actions taking place to resolve them is critical to maintaining a good relationship with sponsors and management.

The most common forms of communication of these topics are via a weekly and monthly report. The weekly report should be an ongoing stream of top-level topics that would be most important for the sponsor and management to know. The weekly report should read like a series of headlines from the evening news, with a line or two of detail on each topic. There should be a continuing storyline so that the reader can follow each topic until its conclusion. Skipping or eliminating a topic in any given week can raise questions or concerns, especially if it involved a problem. People naturally tend to assume the worst, when there is silence about a problem for more than a week. With any problem being reported, a corrective action plan should accompany the problem description. Progress or status of the corrective action plan should be given each week, so the reader understands how this is progressing (or not). Once the problem is resolved, the resolution should be reported, and that topic can end. During the development cycle, there is never a time when a running story line about a problem doesn't exist. Flight projects always have problems! The amazing part of flight projects is that great teams come up with ways to solve them.

The monthly status report is the other common form of project status communication to sponsors and senior management. This is a more in-depth report of technical and

programmatic progress than the weekly report. The monthly status review should include topics such as the following:

- "Stoplight" or red/yellow/green rating sheet
- List of major accomplishments
- Monthly and cumulative cost information (plan vs. actuals), staffing report (plan vs. actuals)
- Updated schedule summary
- Status of cost and schedule margin
- Summary of technical margins such as power, mass, processor throughput, memory, project risks, and mitigation status
- Any specific problems/issues/concerns and their corrective action status

There is usually an accompanying presentation of the project's monthly status report to the project stakeholders, generically known as the monthly status review. The monthly status review is a time for the project manager to give the most accurate accounting of progress to his/her stakeholders. It is a time and a context for the project manager to have a dialogue with the sponsor or senior management about how things are going and what, if anything, they can do to help. If the information presented is not accurate or complete, this conversation cannot happen in a meaningful or timely way. The opportunity for advocacy in resolving problems could be lost or delayed. It is essential that all the cost, schedule, risk, and technical status be accurate and complete. Direction or decisions from this review can either help or hurt project progress. The best chance for help is to provide good information upon which to base such decisions. This also includes risks and current mitigation status. These are the plans the project has in place to avoid problems in the future. Aside from discussing current problems and corrective actions, the risk discussion is the next most important conversation. Addressing risks which could turn into real problems and discussing mitigation activities to resolve them is critical to effective project management. Communicating risks across the project team and providing status to sponsors and senior management kept everyone informed and attuned to prevention and resolution.

Project teams also rely on effective communication to prepare for major milestones. These include key reviews such as System Requirements Review, Preliminary Design Review, Critical Design Review, Key Decision Point reviews, Launch Site reviews and Operational Readiness Reviews. The project manager needs to provide a plan for developing presentation material and conducting dry runs. A written outline of the presentation material consistent with review requirements is essential. Project teams are most effective when a clear direction is given. The review outline should be as detailed as necessary to ensure all review requirements are met. It is beneficial to conduct a "flip through" with the project team before the "dry run." The flip through is a session where presenters simply sit with the project management team to review their slides, without actually giving the presentation. This is strictly a check on review content, both missing and redundant material. Comments are given to each presenter, which may require adjustment to the presentation content. The dry run is conducted about a week later, where each presenter then actually briefs his/her slides as if presenting at the actual review. The project management team can then feed back comments on the verbal presentation and delivery, as opposed to chart content. Providing clear guidance to the project team is critical to a successful milestone review.

Once the review is completed, the review team or sponsor will provide feedback to the project manager concerning the quality of the review and any resulting action items. It is important for the project manager to convey that information back to the project team and senior management. Teams need constructive feedback to move forward effectively. They also need feedback for self-assessment and satisfaction. The project manager should take care to provide feedback promptly and with gratitude for the effort expended. Team members look for feedback from their leader, and a simple acknowledgment of the hard work they put in is important. Any deficiencies in the review must also be addressed, without publically singling out any individual(s). Teams need to hear both positive and negative feedback when given. The delivery of negative feedback can make all the difference in how it is received. When provided in a tone which highlights areas for collective improvement, the message can be taken much differently than if given in a condescending or harsh, directive tone. The ultimate goals are for the problem areas to be addressed appropriately. Most times this can be achieved without alienating team members.

In the space flight industry, the schedule is always important and it is typically a driving factor. After a major milestone success, teams should be allowed to enjoy their intermediate milestone achievements for a short period, then prepare for the next task. The project manager may take that opportunity to have a project social event to celebrate success to date. Nothing communicates thanks like free food and drink! At that time, it is appropriate to acknowledge individual efforts, both publicly and privately. Organizational culture dictates how individual achievement and effort are recognized. Many organizations celebrate collective achievements such as group awards in a public way and individual achievements such as cash awards in a private way. Achievement awards can vary from bonuses to pay raises or award certificates, depending upon the organization. Generally speaking, any form of award is usually welcome by the recipient. Acknowledgment of a hard effort in any form is a good thing.

Performance coaching is another important element of project communication. Organizations usually have some form of annual performance assessment of its employees. Project managers may have direct or indirect input into this process. In some organizations, project managers provide direct feedback on employee performance to the individual. In other organizations, this feedback may be given to the line management to fold into its performance assessment from the employee's home organization. Either way, it is incumbent upon the project manager to provide accurate, prompt, and thoughtful feedback to the team member. The feedback should highlight both positive accomplishments and performance, as well as areas for improvement. Once again, the delivery of the message is vital. Good performance should be acknowledged in a positive way. Specifying actions or achievements are helpful, as these are the things you wish the team member to continue to replicate. Underperformance should be provided in an open and honest way, but always in the context of providing a path forward for higher level performance. Providing examples of areas for improvement are helpful, especially when coupled with ideas for learning from others or training and experience opportunities to show the team member support.

As described in this chapter, effective project communication takes many forms in various venues to many different stakeholders. It is the cornerstone on which projects are built. Projects with effective communication are much more likely to succeed than those that lack a consistent and appropriate means of communicating across the team and stakeholders. Timely information delivered in the proper way is empowering to all who receive it. Finding the right balance of level of detail and frequency of information communicated across the project is the job of the project manager and it is one of the most important ones.

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Leadership 101

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COMMUNICATION IS FUNDAMENTAL TO HUMAN EXISTENCE

Introduction

A leader knows there are countless definitions of leadership.

An excellent definition is "the ability to mobilize different resources to achieve a common, envisioned goal." This definition is effective because of its brevity and impactful words. "Mobilize" provides a sense of urgency and inspiration. "Different resources" includes the people, facilities, equipment, budgets, and other assets needed to achieve the objective. "Common, envisioned goal" conveys the idea of a team, in consensus, with an agreed-upon vision and an end state.

A lengthier definition of leadership is "the ability to inspire our staff, influence outcomes, confidently shape envisioned futures, and implement the change necessary to enhance the impact of our critical contributions to critical challenges."

Both definitions emphasize that a leader must be able to marshal resources and be the force that positively affects the future.

This chapter discusses the impact of a leader, the differences between leading and managing, common traits of very effective leaders, situational leadership, and how to form and maintain high-performing teams. This chapter also covers how to deal with difficult people, how to personalize your own leadership style, and how to enhance your own personal performance. At the end, a case study is discussed.

Impact of a Leader

Leaders are expected to work together across programs, technical groups, and other artificial boundaries to fully leverage an enterprise's capabilities. Leaders at all levels must demonstrate influence in the following areas:

Staff development—Actively team up and engage with staff to evaluate areas for growth, establish development plans to address those areas, identify opportunities for future growth, and provide coaching and mentoring along the way.

Organizational competencies—Ensure that the depth and breadth of the staff meet the current and envisioned future needs of the organization.

Mission effectiveness—Develop goals with the concomitant vision to achieve them; then be the force that influences innovative, affordable, timely, and effective solutions to critical issues that arise along the path to these goals.

Resources—Organize, train, and equip the staff to ensure that, as a team, objectives can be achieved. To do this, define, engineer, and build the infrastructure necessary to enhance staff development, organizational competencies, and mission effectiveness by improving training, facilities, laboratories, computing resources, and other essential tools. Work within constraints to optimize the overall investment strategy through collaboration and innovation.

Functional responsibilities—Deftly execute the management responsibilities unique to the leadership position.

Leadership versus Management

Leadership is different from management, yet they are complementary. Ideally, leaders are good at both and know when to do one or the other. Organizations with strong leadership and weak management are no better than organizations with active management and poor leadership. The challenge is to combine strong leadership and active management into a unifying force that moves teams toward the envisioned future. Some people are good leaders, but poor managers, and vice versa. Management can be viewed as an activity that copes with the complexity of day-to-day activities by bringing order and stability to the current chaos. Leadership is about dealing with change or forcing the change that will steer a team toward an envisioned future. Hence, managing involves minimizing risk, avoiding conflict, being reactive but logical, being in control, having subordinates, planning, budgeting, organizing, and staffing. Alternatively, leading involves taking the risk to achieve that envisioned future, using conflict to improve the situation, being proactive, appealing gut feel and experience, being passionate, having followers, setting direction, and aligning people and other resources with the envisioned future. The best leaders know when to lead and when to exercise management skills.

Effective Leadership Observations

Experience and research indicate that most effective leaders have consistent and shared traits:

- People are their top priority—they do everything they can to take care of them so they, in turn, can focus on the job.
- Their ethics and integrity are unquestionable.
- They are exceptional communicators.
- They remain calm at all times.
- They inspire their staff and are visionaries.
- They are resilient, bold, and courageous.
- They are meticulous planners.
- They are always prepared for change and are usually the force behind the change, steering the team toward a common goal or envisioned future.
- They know what needs to be done and what is best for the enterprise.
- They know who the key stakeholders are.
- They are adept at creating consistently successful teams.
- They set clear expectations for their team.
- They excel at delegation and hold their people accountable.

- They run productive and efficient meetings.
- They make decisions in consensus with their team, but, if necessary, will make a decision unilaterally.
- They maintain a chain of command, so communications are consistently fluid inside and outside the team.
- They never focus on problems, but rather on opportunities.
- They use we and us, and never me and I.
- They frequently walk around to see how it is going in "the trenches" with the "team on the ground," and they always solicit their opinions.
- They own the problem their boss has given them, they take the blame when there are failures, and they spread the praise to everyone else on the team when there are successes.

Studying these common traits will provide the knowledge needed to make impactful decisions, convert that knowledge into appropriate actions, and ensure accountability throughout a team and organization. Understand that few leaders possess all of these traits all the time—but they can surround themselves with staff in high positions who have some of the traits that can balance their weaknesses, thereby making the team stronger and more complete.

Situational Leadership

DiSC* is a behavioral assessment tool based on the theory of psychologist William Marston, focusing on four clearly different behavioral traits (*d*ominance, *i*nfluence, *s*teadiness, *c*ompliance). Many organizations use this tool so staff can learn about themselves, and how to deal with others when interpersonal relationships are involved. DiSC can be used to help build teams, to develop more effective leaders, managers, and individual contributors, to help with conflict management, and to improve coaching, mentoring, and counseling. It is included in situational leadership because by knowing one's behavioral style and that of others, DiSC can quickly help get teams aligned among individuals. A brief summary of observations based on DiSC follows:

- A D-person emphasizes taking charge and accomplishing results. When talking with a D, give them the bottom line and be succinct.
- An i-person emphasizes influencing others and relationships. When communicating with an i, share experiences and minimize details.
- An S-person emphasizes cooperation and dependability. When communicating with an S, be personal and avoid being confrontational.
- A C-person emphasizes quality, accuracy, and competency. When talking with a C, highlight facts and details.

* DiSC® is a registered trademark of Everything DiSC, a Wiley Brand.

Forming an A-Team

Leaders need to build teams. How does a leader ensure the team is high-performing and sustainable? Getting the correct people on the team (and keeping the wrong people off the team) is key.

To form this A-team, a leader and current teammates are the best recruitment tool. Leaders should make it their job to communicate their goals, their vision, their work environment, and their envisioned end state in so inspiring and motivating a manner that folks want to be part of it. A leader should ensure the team is diverse in technical/programmatic skills, behavioral traits, and thought patterns. It is essential to provide the necessary organization, training, equipment, morale building, and even discipline, so the team has the necessary tools to excel. Leaders should address the "little things" so the team can focus on their jobs, find weak spots in the team and fix them, thereby raising the standards of what is expected of individuals and the team as a whole. Once a team accepts what used to be branded as exceptional is now just ordinary, they will be outstanding compared to other teams every day.

Once a team is established, a leader must be able to negotiate their time with them, their line supervisors, and the program managers for whom they work. Once those agreements are reached, either in writing or by the shake of a hand, everyone should be held to it and the activities tracked relative to progress. If necessary, a leader must renegotiate to ensure alignment between the team's effort and the tasks they must accomplish.

As the team matures, leaders and subject matter experts will emerge within the team; these leaders and specialists should be assigned major roles. They should be given tasks and the autonomy to conduct them. They should be allowed to handle the roles they have been given. They may not do the job in the same manner as another leader, but as long as they ethically meet your goals, objectives, timelines, and budgets, there is no need to meddle with how they do it. They should be trusted to do their jobs, and be ensured they have the support to address issues that arise.

To maintain this high-performing team, a leader needs to understand what makes emergent leads and subject matter experts tick. Odds are it will not be money. Usually, it is job satisfaction and peer recognition. By creating a culture of impactful, exciting, challenging, motivational work with the right leaders and subject matter experts in major roles, a leader can maintain this high-performing team. Of course, when apparently exceptional work is consistently achieved, the team members could be financially rewarded for their real achievements. A leader must resist the institutional pressure to spread rewards broadly; it is demotivating to highly performing staff and those who aspire to achieve such recognition. Rather, fewer, more meaningful rewards should be provided. It took decades of thinking, planning, innovating, designing, engineering, building, and nearly a decade of full flight operations before the NASA/APL New Horizons spacecraft raced past Pluto on July 14, 2015, astounding the world with its images and scientific discoveries. That was the real achievement, which should be rewarded. There is no need to reward an individual or a team for simply meeting job requirements.

An individual will not be a leader forever. Eventually, opportunities such as retirement, transfer, promotion, or simply choosing to step down to an individual contributor role will present themselves. A leader of a highly capable team must ensure that training for replacement is part of the ongoing activities. One must find that staff member (or members!) who wants to be a leader, and coach them, mentor them, and train them so that when opportunities for leadership change arise they can be embraced knowing that the team will

continue to be successful. It has been observed that many average leaders spend 90% of their time coaching and mentoring the bottom-performing 10% of their staff. The best leaders spend 90% of their time coaching and mentoring the top-performing 10% of their staff. Concentrating on the top performers enables an organization to have a deep pool of viable future leaders.

Dealing with Difficult People

All leaders eventually have to deal with a difficult staff member. Don't get emotional. Stay rational. Remember, challenging behavior at work can reflect issues in a person's personal life. Or perhaps the concerned staff simply do not have the technical or programmatic wherewithal at this moment to get their current job done. Have empathy and be understanding. But hold them accountable to the same standards as everyone else. Have crucial conversations with that person, realizing that difficult, direct conversations had early can prevent the need for significant action later, such as suspension or employment termination. If faced with unreasonable verbal or written criticisms (or worse, verbal or written assaults), ask the staff member what exactly he/she is upset about to demonstrate an interest in communicating rather than in arguing. Offer the staff member your best guess as to what he/she is feeling, and ask for feedback. This demonstrates a willingness to understand the person's frustration. Resist the urge to fight or win the argument. Listen and ask frequent questions, as this leads the staff member to form better conclusions and gain perspective. Finally, don't be afraid to remove the difficult staff member from the team, and don't be apologetic for it. Sometimes, even exceptional staff members are just not right for the current tasks or team and can perform at a high level in different circumstances.

Personalizing Leadership Style

A leader must understand the implications of their personal history, quirks and all, better than anyone. Emphasize what works best, and be aware of strengths and weaknesses. Continually read other articles and textbooks on leadership and adopt the new skills learned. Carefully observe leaders and learn from them. Distil observations and tailor them to your needs. Always control moods, so as to project a positive, but realistic, outlook; have empathy to better understand other people's emotions, and develop the social skills necessary to effectively build rapport with others to help move them in the right direction. Ask peers, supervisors, and subordinates for perspectives and advice on traits to emphasize, change, and initiate as a leader. Have frank conversations with them and learn from these discussions. Enlist a mentor to help identify your weaknesses, and repeat this process at least yearly and measure improvement. Without this measure of improvement, it is not possible to effectively gauge progress. Remember, successful leaders not only train their replacements, but also train their replacements to be successful. So delegate tasks to subordinates and let them do their jobs without constant oversight. This act of empowerment is key—it indicates trust in them. While they might not do the task as expected, it does not mean they are doing it wrong.

Enhancing Personal Performance

Getting proper rest, diet, and physical activity is important. Ensuring a leader and a team always follow the organization's core values is also key. Staying up to date with current technologies, taking additional training, furthering education, and getting a mentor are important as well. Consider the following three illustrative examples.

A mentor once told a friend of mine that the key to work-life balance was, in moderation, to take care of himself first, then his family and friends, and then work. At first, my friend thought this was selfish and completely backward—he followed the mantra of "job first, then the staff, then himself." But his mentor said he needed to use common sense and care of himself first and stay healthy so he could enjoy his friends and family. If he were ill or missed family and friends, he would not be able to focus on work. This general officer in the military lived his life this way and insisted that all of the staff did too. My friend has used that phrase on his subordinates and peers ever since.

Another example that may help improve one's personal performance is to ask the human resources department to perform a "360" on oneself. This is very detailed feedback about an individual's work performance from superiors, peers, and subordinates, and it frequently highlights chinks in one's armor that must immediately be corrected. This "360" can be tailored to leadership, management, or technical skills, or— better yet—all three!

A final example to improve personal performance is to always keep the boss's inbox empty. This does not mean keep the boss out of the loop. Rather, keep the boss up to speed on assigned tasks via regular status updates, but do not go to the boss with problems for him or her to solve. Instead, work out the problems at the lowest level possible. If the problem cannot be solved, go to the boss with the issue, and present the boss with several options and a recommended way ahead. A corollary to this is to regularly ask the boss if there is anything you can do for him or her. By taking something off their plate, they can "play up" and have more time to work on other key issues. Similarly, it gives you and your team a new opportunity to "play up" to the next level, allowing both to potentially gain more insight into the enterprise's vision, strategy, and execution priorities.

Leadership Lessons from the New Horizons Flyby

Consider NASA's New Horizons flyby of Pluto that occurred on July 14, 2015. The fastest spacecraft ever launched, New Horizons traveled for more time and distance than any mission to reach its primary target. New Horizons was launched nearly a decade earlier, on January 19, 2006 (Figure 18.1). Planning for the mission began decades earlier than that. Dr. Alan Stern of SwRI was the mission's principal investigator and the leader of this monumental effort since the late 1980s. JHU/APL managed the mission for NASA, and designed, built, and operated the spacecraft. Additionally, there were navigation, operations, science, education and public outreach, and communications teams associated with the mission.

During the 1-hour period immediately before the closest approach on July 14, 2015, 42% of all government web traffic was going to NASA web pages. Immediately after the



FIGURE 18.1
The New Horizons spacecraft was launched on January 19, 2006, from Cape Canaveral, FL, via an Atlas V rocket. (Courtesy of NASA, Washington, DC.)

successful flyby of Pluto, there were more than 2800 media reports, and Pluto's image was featured on the front pages of nearly 450 newspapers. There were 908, 423 social media posts on #PlutoFlyby, and even President Obama shared a Pluto photo in a congratulatory tweet. It was a great day, as the President tweeted, for discovery and American leadership (Figure 18.2).

But in February 2015, it became apparent that this July 14, 2015, flyby would be the largest public event (~2000 guests) ever hosted at JHU/APL, and some concern began to settle in with the management. Quickly, a guest operations team had to be formed to work logistical issues ranging from guest lists, invitations, traffic flow, catering, parking, security, additional WiFi for the crowds, and signage around the campus and local area to sewage fluency out of the conference center. A leader was hired to run this guest operations team who had no NASA experience but plenty of leadership experience. Below is a brief summary from his log and after-action report. Note aspects in these summaries consistent with the leadership suggestions from this chapter:

- Met with my boss to determine where we are now, what does "good" look like on July 14, who are the key stakeholders I must keep in the loop, and what is best for the NASA, SwRI, APL, industry-partner team.
- Met with the key stakeholders and asked them where they perceive us to be right now, and what "good" looks like to them on July 14.
- Working backward from July 14 to the current date (March 10), developed a detailed action plan as a result of these initial meetings, making it as detailed as possible and highlighting the gaps as I understood them.
- Formed a diverse 15-person team, including subject matter experts in event planning, security, facilities management, plant engineers, and IT personnel. I also

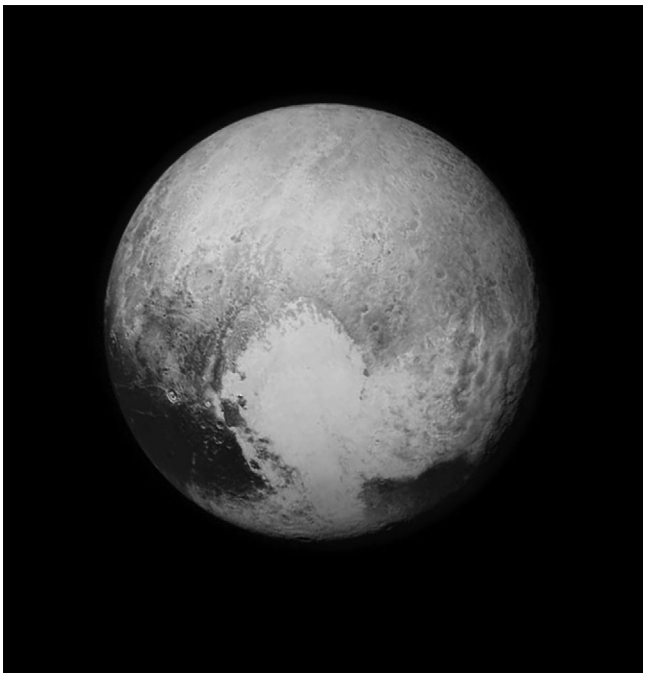


FIGURE 18.2
Pluto fills the frame in this iconic image from JHU/APL's Long-Range Reconnaissance Imager from NASA's New Horizons spacecraft, taken on July 13, 2015. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) managed the mission for NASA, and designed, built, and operated the spacecraft. (Courtesy of NASA, Washington, DC.)

ensured that the folks on the team could cover my weaknesses (never worked with NASA, not an engineer, knew few people on the mission team). Negotiated time with them and their bosses. Had the principal investigator and several senior staff from NASA on the team as well, along with leads from other teams (science, education and public outreach, communications) to ensure we were in sync.

- Held a kick-off meeting. Let everyone know what our bosses thought mission success looked like. We went around the table and introduced ourselves and I highlighted the skills each person had and what roles they would play on the team. Once we were all base-lined with the big picture, we discussed my initial action plan. In consensus, we edited it, set priorities, set deadlines, and assigned tasks to teammates. It was now our action plan. It became apparent that we needed additional staff with additional skillsets, so I asked the team who from the enterprise they recommended; we added 10 more staff to the team that week, all chosen by existing team members.
- Held weekly meetings where we reviewed the primary goal each time, then the assigned tasks, and updated our action plan. When problems came up, the team members were exceptionally adept at solving them on their own or within smaller teams, and just letting us know what they did at the next full team meeting. They relished that level of autonomy. When difficult problems arose, we debated them and came to a consensus, remembering what our primary goal was (success of the science team).

- If meetings could end early, we ended them. If meetings were going nowhere, we killed them.
- Met twice per week with a few select staff members on the team who became sub-team leaders: the communications lead, the event planner, the IT lead, and the security lead. These additional meetings were necessary to manage the chaos. They, in turn, ran their sub-team meetings. This metamorphosis from one large team to one large team with smaller, focused sub-teams took about 6 weeks to evolve and worked exceptionally well.
- Met once per week with my bosses to ensure they were on board with our progress, and if there were other issues we needed to solve.
- We had numerous personalities on our team, and in our chains of command inside and outside our team. Situational leadership was crucial in knowing how to deal with different folks. In hindsight, I should have more directly dealt with a difficult person on another team whose work behavior was negatively impacting the momentum of our team. My lack of quickly dealing with this personnel issue led to some unnecessary work and distractions that our team could ill afford.
- Established swim lanes early and often with the other teams, so we were in sync and not overstepping our boundaries. The guest ops, education and public outreach (EPO), science team, and communications team all worked in parallel on this event, and the team leads met regularly to discuss issues. Priority 1 was the science team—they had to succeed—followed by EPO, then communications, and finally us.
- Ensured key leaders understood what was going on—and why, when, where, and how. Key leaders and team members were dispersed, sometimes all over the world; just because someone was in a group telephone meeting did not necessarily mean they understood what was going on; nor did it mean their bosses were aware of salient facts. We took the extra step to verify that key decision-makers were aware of and understood the situation with face-to-face meetings whenever possible.
- The team was good in times of chaos and adapted well to change. At times, we could see stress levels rising high, but we took those affected staff members aside and reminded them that we could not convey hysteria—we just needed to remain calm. Some time off would have been nice, but in this case, that needed to wait until after July 14.
- When we were about 3 weeks out, we had a series of dry runs, each one more detailed than the previous one. Seven days prior we conducted as complete a dress rehearsal as possible. These dry runs showed flaws in our plans and allowed us to be better prepared for the main events held on July 13 and 14. Five days prior to the events, our last meeting simply consisted of the team quizzing each other on what ifs: what do we do if we lose all power (yes, we had backup generators), what do we do in a security incident, or what to do in the event of a large food-poisoning event.
- When it was all over, we did prompt monetary awards for high achievers, ensured the record books balanced financially, had two recognition dinners, had an over-arching after-actions review so if there is a next time we shall not repeat historical mistakes, and all took some much-needed vacation (Figure 18.3).



FIGURE 18.3
New Horizons team members, guests, and media countdown to New Horizons' closest approach to Pluto at JHU/APL in Laurel, MD, on July 14, 2015. It took leadership at all levels, and across many organizations, and several decades, to make this a reality. (Courtesy of NASA, Washington, DC.)

Summary

This chapter has defined leadership, and discussed the impact of a leader, the differences between leading and managing, traits of very effective leaders, situational leadership, how to form and maintain high-performing teams, how to deal with difficult people, how to personalize leadership style, and how to enhance personal performance.

Here are three simple takeaways:

1. Create an envisioned future, get staff onboard, and then take care of employees so they, in turn, can work efficiently as a team to get to that envisioned future.
2. Communicate promptly, with no borders and in all directions.
3. Use the common leadership sense learned from this chapter (and from other sources), and always remember to ask staff, especially those "on the ground," for their opinions and recommendations.

If a leader executes these three takeaways, staff will feel empowered, and everyone will have a common, shared view of where they are now and where they need to be. Without a common, shared view between leader and team, and key stakeholders, the envisioned future will not be attainable. Some recommended readings are listed in the Reference list. They are generically grouped by ethics [1], strategy and results [2,3], leadership lessons and examples [4–6], dealing with difficult issues [7], personal performance [8], and project management [9], all of which are key to being a successful leader.

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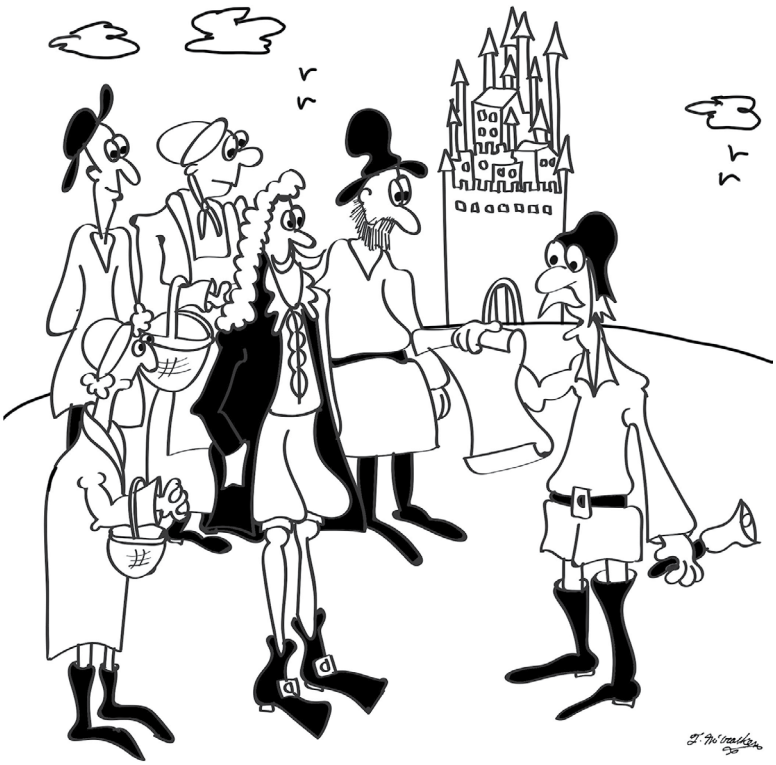
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Human Resources

Rebecca Casanova

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THE VILLAGE BLAST REDUCES
GOSSIP AND MISINFORMATION

Introduction

A good project manager understands the technical aspects of the work, but a successful project manager understands the need to master the nontechnical parts of the job too. There are many things to learn about this role, especially when joining a new organization. But even with a current employer new challenges and experiences will be encountered.

First, the organizational structure plays a significant role in the ability to manage a project. Understanding the advantages and disadvantages of the different organizational structures and their impact on leadership and management is critical to the success of the project and of a team.

Second, leaders and managers do not operate alone within the organization. It is important to see the organization as a system, understand how the subsystems integrate and relate with each other, how these things impact a leader's role, and leverage power for the benefit of the system and the team.

Third, managing the workforce in a team is important. Acquiring, developing, and retaining the right talent to create a high-preforming team are integral aspects to the success of the work. An important business partner available to project managers is human resources (HR). A common denominator in the successes and failures of projects is the people. Leveraging HR is important to help manage and deal with difficult staff situations.

This chapter discusses different organizational structures, the importance of seeing organizations as systems, the role and power of the project manager within the system, and the role of HR as a partner.

Organizational Structures

As organizations determine their purpose and business strategy, they also establish ways to accomplish goals. Technical organizations strategically structure their internal resources in a variety of ways to achieve the highest level of performance. Their structure defines how functions and tasks will be assigned through the organization [1].

Organizational structures consider job design, how the work needs to be coordinated, how the work needs to be delegated, how many staff should report to one manager, and what chain of command or lines of authority are established. This allows the organization to have multiple groups and different functions working together.

As external factors impact the organization, they will evaluate the need of restructuring their resources and making changes accordingly [2]. As such, there are several questions any organization should explore prior to establishing a structure. Kerzner believes that organizational forms have advantages and disadvantages based on technology and social systems.

There are numerous ways to structure an organization and it is important to understand their advantages and disadvantages, and the impact they have on project management. Three of the most common organizational structures in technical organizations are functional, divisional, and matrix. The latter combines functional and divisional elements.

A functional structure focuses on the specialization of the staff and the work that needs to get done. For example, a functional organization may be divided into areas such as science and engineering. Each of these functions houses specializations under them. That is,

the science division will focus research based on business strategy like planetary research or earth science, while the engineering division will cover areas including mechanical or electrical elements of a project. The functional structure is hierarchical, allowing for standard processes and creating specialized staff.

Advantages of a functional structure are that staff are proficient in a particular field and they can learn from each other. Also, it is easy for staff to know where the chain of command begins and ends in the organization as the hierarchy is clearly established [3]. Disadvantages include the existence of silos that may lack the flexibility to work effectively and efficiently across different functions. This makes the structure resistant to change as interactions with other areas of the organization are nonexistent [3].

Managing a project in a functional organization has the challenge of managing silos. Because each function is managing a piece of the project, there are several functional managers who can report on their own work, but are unable to provide the status of the "big-picture" of the work. This can create conflict across functions and delay progress of the work.

A divisional structure focuses on the division of work and employees by project or customer. For example, an organization may have multiple projects supporting the same customer, but each one of the projects will have their own supporting units like business, quality, marketing, engineering, and science.

Advantages of such a structure are that each project receives unique and customized attention from each unit as they share one common goal. This makes it easy to coordinate across units, and makes the work more specialized toward a particular project [3].

Disadvantages include duplication of effort in every project and inefficient use of resources, staff with similar technical backgrounds will have less interaction, and it creates competition within the organization if they support the same customer [3].

Managing a project in a divisional structure facilitates communication and understanding on the status of the work. All the units in support of the project work together and this tends to avoid delays in the delivery of the product. On the other hand, once the project is over, these units would need to be absorbed by other areas of the organization or be eliminated.

A matrix organizational structure is a combination of functional and divisional structures. For example, an employee will have two supervisors. One is a direct or functional supervisor and the other is a divisional or project manager. This structure is very common in technical organizations because it is an effective and efficient use of resources. That is, an employee can be an expert in a particular function but that expertise can be shared across projects.

Advantages of this structure are the integration of function and division, making the work a priority and cost-effective due to sharing of resources. It also allows the organization to have better oversight of the product and be in a better position to determine when and where to reallocate resources [3].

Disadvantages include having employees report to more than one manager. In some instances, employees struggle with balancing responsibilities and their performance may decrease. The control of the work becomes difficult if the two managers cannot interact with each other effectively. This also impacts the staff and increases their level of stress and ability to prioritize [3].

Managing a project in a matrix structure lets the project manager have more visibility into the work and the people. It is certainly cost-efficient and effective because it integrates all the resources required to promote a team environment. On the other hand, managing under this structure requires project managers to have effective communication skills with all staff and areas of the organization when positive and negative situations arise.

Organizations as Systems

Organizational structures are complex and serve as a simple visual representation of the different boxes in the organization and how they link to each other. But what they do not show is how they relate and integrate to each other to be successful.

A project manager must be constantly aware of the bigger picture and have a broad perspective. In this role, it is helpful to think of the organization as a system with a variety of subsystems that are related and integrated. Understanding them will reveal patterns of relationships and patterns of processes.

To not see or understand the system creates serious problems. There can be lack of partnerships leading to misunderstandings and assumptions promoting lack of collaboration and hindering the success of the organization [4].

Traditional Project Management Organizational Structure

As organizations create their structure, programs or projects within the organization create their own structures too. The functional hierarchal structure is most common for project or program management in the Aerospace community. Figure 19.1 shows a generic version of such a chart. This generic functional chart can be tailored for smaller instrument builds and for larger observatory programs. The organizational structure of a program developed around the team that a project manager engages is a key component of successful projects. The structure must reflect the work, the team leading the work, and the correct hierarchy to reflect team members joining and leaving a project throughout its execution.

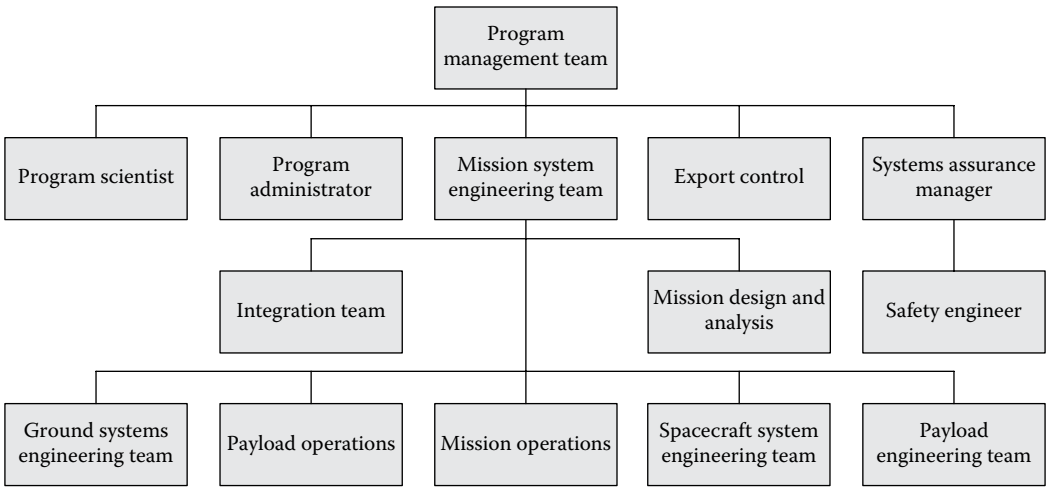


FIGURE 19.1
Generic organizational chart (by function).

An example of a large program is the James Webb Space Telescope (JWST), which has a budget of more than $8 billion [5]. One should not underestimate the size and complexity of such a large program and how these characteristics are reflected in the organizational structure of the team. JWST involves 14 countries, partners, and contractors in 21 states (EPO in 41 US states). NASA is the lead partner of Webb, with significant contributions from the European Space Agency (ESA) and the Canadian Space Agency (CSA). Northrop Grumman Aerospace Systems (NGAS) is the main NASA industrial contractor responsible for building the optical telescope, spacecraft bus, and sunshield, and for preparing the observatory for launch. The Integrated Science Instrument Module (ISIM) complement is as follows:

- The mid-infrared instrument (MIRI) is provided by a consortium of European countries and the ESA and the NASA Jet Propulsion Laboratory (JPL) with detectors from Raytheon Vision Systems.
- The near-infrared spectrograph (NIRSpec) is provided by the ESA.
- The near-infrared camera (NIRCam) is built by the University of Arizona working with Lockheed-Martin.
- The near-infrared imager and slitless spectrograph (NIRISS) are provided by the CSA [6].

To manage such a diverse, complex, and large program, the organizational structure must be clearly delineated (Figure 19.2).

For each element of the organizational chart one can drill down into the subelements and trace up through the management chart. Clear lines of authority support good communication across managers, technical providers, scientists, users, organizations, contractors, partners, and customers (Figure 19.3).

Bottoms, Middles, Tops, and Customers

Dr. Oshry's book *Seeing Systems* explains that in a system all the people are top, middle, bottom managers, and customers. He calls these "conditions" and, because members are part of a system, they are continuously moving in and out of these "conditions" whether they realize it or not.

These conditions are defined as follows [4]

- Top managers "shape the organization" and live "in a world of complexity and accountability" and are "accountable for the successes and failures of the system."
- Middle managers "service and manage various parts of the system" and "struggle to survive in a tearing world. They are pulled between you and others…they experience simple requests *from* you and others as complex tearing *between* you and others."

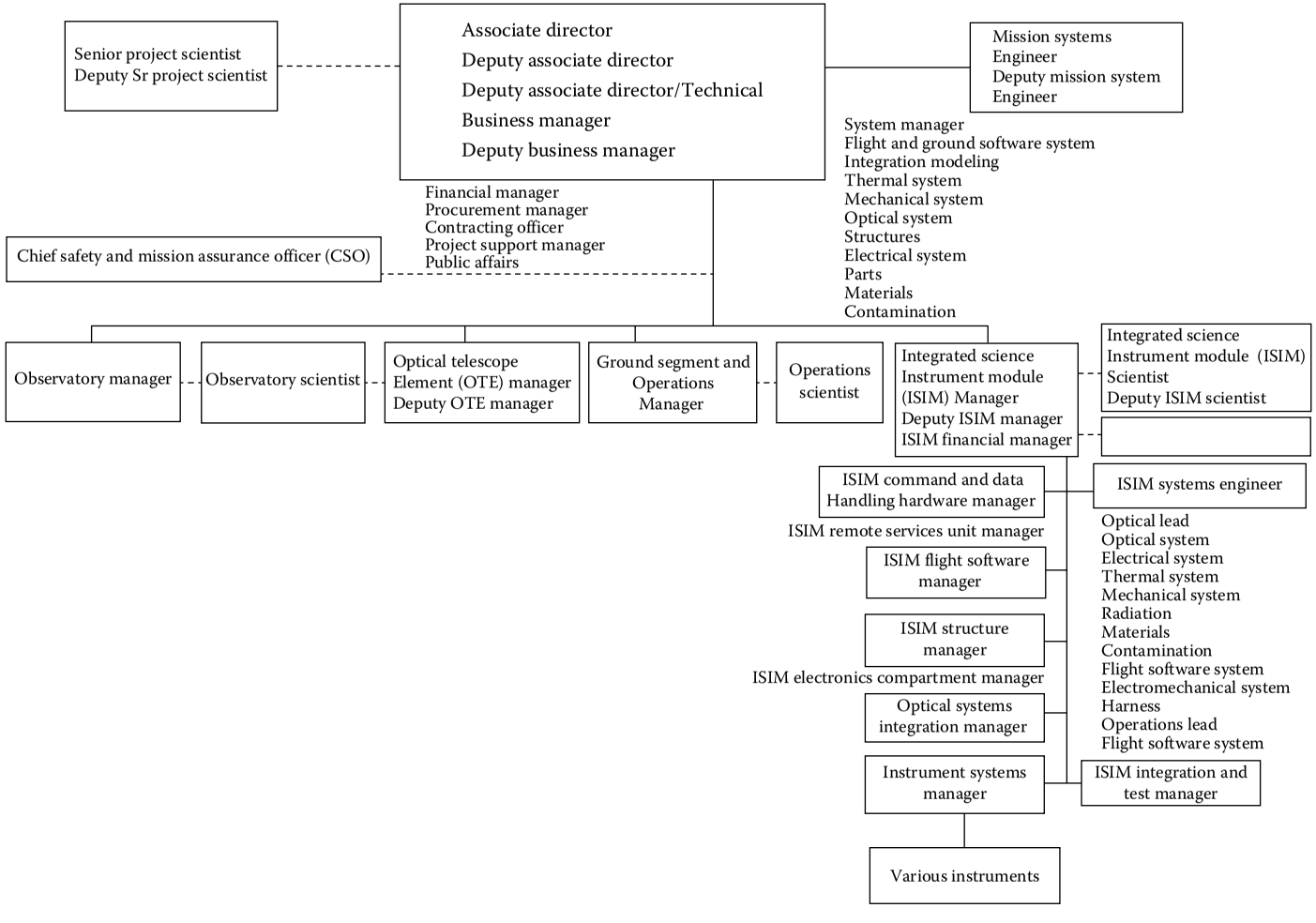


FIGURE 19.2
This is derived from the larger JWST organizational chart showing just the structure to manage the instruments.

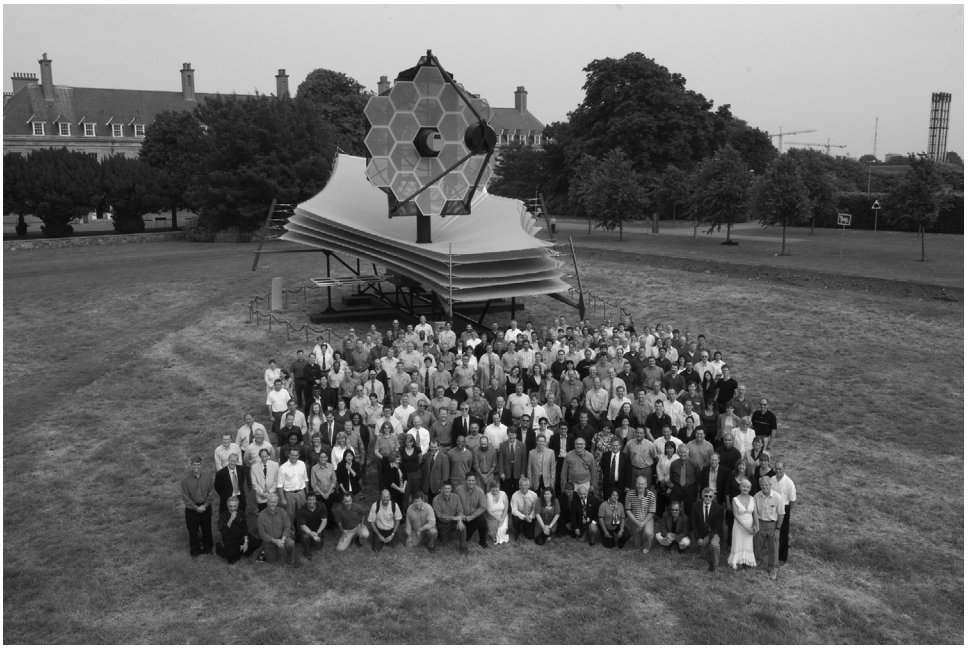


FIGURE 19.3
JWST full-scale model in 2007 with a fraction of the staff at Dublin, Ireland. (Courtesy of NASA, Washington, DC.)

- Bottom managers produce the outcome of the work and "struggle to survive in a world of invisibility and vulnerability." They can be invisible to top managers, yet are the most impacted by their decisions.
- Customers may "live in a world of neglect," lacking attention and experiencing delays in what they want to feel satisfied.

Three things every project manager must recognize about all these conditions [4]:

1. None of these conditions can work without each other.
2. A project manager's condition will be impacted by their interactions with others.
3. Every condition has its own level of power.

Middleness as a Condition

Gaining insight into the world of a top/middle/bottom/customer, broadens one's perspective of the system and makes it possible to identify ways to interact effectively. Seeing the system provides insight into the patterns of relationship. A project manager may identify with the role of "middle manager," always torn between the needs of the customer, what others can provide, and limitations imposed by others.

Oshry explains three classic patterns of relationship that a project manager will encounter [4]:

1. *Provider/Customer*: The customer will view the project manager as a provider of a product, and the project manager will want to provide the customer with a good-quality product, on time, and on budget.
2. *End/Middle/End*: The ends always have conflicting agendas and look at the middle to sort it out. One end could be a top manager and the other end could be the customer. Project managers will find themselves in between these, and others.
3. *Top/Bottom*: The staff in a project will view the project manager as the top manager. To them, "the project manager will have a designated responsibility for the system or a piece of the system." In turn, the project manager will see them as bottom because they are subordinates or team members.

Project managers master the system when they master their level of power as the middle. Oshry's advice is to do the following [4]:

1. Avoid making other people's problem your own—empower others!
2. Keep your own mind—stay independent in thinking and focused on the task!
3. Be a top and take responsibility—avoid escalating situations and take ownership of tough decisions.
4. Be a worker and live with the consequences—don't pass bad decisions from the top managers to bottom managers!
5. Coach—empower and empathize with others!
6. Facilitate solutions—help everyone have productive interactions!
7. Integrate—think of the system!

A High-Performance Team

In recognizing the system and understanding the conditions, it is clear that project managers do not work alone. Helping a team navigate through these challenges requires a project manager to be transparent by sharing broad perspectives, and to give them autonomy by empowering them.

Experience shows that all project managers wish for the same thing—to form a team of outstanding performance. But when asked to define this, their response is often a variant of "a team that can solve the most difficult technical problem and get things done."

The issue with this response is that solving the "most difficult technical problem" is hardly ever the problem. A team of outstanding performance, by definition, will have the right talent to do it. What the response is missing is that, in order to call a team one of outstanding performance, "people work" needs to happen through the life of the project team.

"People work" can be challenging, thus the saying: "Being part of a team is great! But dealing with the people is not!" So the question is whether there is an effective way to work with the people and have a high-performing team. The answer is *YES!* All that needs to be understood is what a high-performing team is and the characteristics it demonstrates.

A high-performing team can be defined as a group of individuals who have a clear understanding of the task and their roles, and hold each other accountable. The team knows what they need to do, and agrees on how they are going to do it. It is not about how they will apply their technical knowledge, but what the environment of the team will be to increase job satisfaction and morale, thus allowing them to achieve high levels of performance [7].

High-performing teams have the following characteristics:

- The team knows what will be accomplished and each individual knows their role and responsibility—no assumptions!
- It retains high performers by giving them challenging work—increase job satisfaction!
- It manages low performers—coach them, match them with a complementary skill set, or reassign them to another task!
- It has different incentives and motivators to increase work satisfaction—know what motivates each person in the team!
- It has a leader who is engaged and who proactively removes obstacles that interfere and are detrimental to the work of the team—the project manager's job is to increase team performance!
- It has open, respectful, and honest communication—not afraid of feedback!
- Nobody avoids conflict—it should be a safe environment and conflict can be constructive!
- Members feel empowered and take full ownership of the work.
- They agree on how they will operate and behave as a team—what is acceptable, what is not acceptable.

The question then arises as to how one person can be successful in doing all of this? It is hard but not impossible. The key is to know what resources are available and how to partner with them.

The Role of Human Resources

The role of human resources (HR) in a project or program setting is slightly different from its role in a traditional organization. HR will make sure the needs of the project are met through the people. HR will help project managers with their number one asset, the staff. The three basic needs a project manager will meet with the help from HR are recruiting, developing and retaining staff, and partnering to manage conflict and performance issues [8].

As a project manager, leveraging on HR for recruiting is important because of their expertise in talent acquisition and workforce planning, and in managing, developing, and retaining staff. Engage HR early in the process, without waiting for issues to crop up [8].

Project teams work together for a limited time and encompass a variety of skills and disciplines. Because these teams focus on a single output, they will require expertise and significant knowledge. Partnering with HR will help a project manager find the people with the right skill set—both technical and nontechnical.

Through the recruiting process, the project manager should be engaged with HR in defining the job duties and the required experience. A good recruiting practice is to be part of the interview and the selection process. Depending on the skill needed, it may be time-consuming but the effort spent will be worthwhile.

Usually, staff is selected to work on projects based on technical skills. It is important for the project that staff is also competent in nontechnical skills. This is where HR can be really useful—with training and coaching of nontechnical skills to project staff. The appointment of staff to projects also takes on strategic significance since the career dynamics of allocation to projects is clearly visible. This may influence the ability of the organization to retain employees [8].

The different phases of a project determine the skills that are required at a given time. Fortunately, many technical organizations manage multiple projects, making it easier to transition staff from one project to another. HR also has a role managing this transition of staff at the end of the project. This is also a period when project staff tends to be more anxious, and having processes and practices in place to recognize and manage this anxiety is clearly important not just to the mission area, but to the organization as a whole [8].

The next set of challenges for a project manager is developing and retaining staff. For HR, helping project managers to develop staff begins with the onboarding process. This helps the new hire get acclimated to the organizational culture, ensures they have a clear understanding of their role and responsibilities, and makes additional resources available to them. It also helps the organization because it demonstrates willingness to invest and to engage new staff.

HR can create a customized onboarding program that meets the culture of the organization while considering the needs of the new employee. Ultimately, the goal is to make it a positive experience and one that will help develop and retain staff [9].

A key to retaining staff in the organization is ensuring that employees have opportunities to work in projects that are challenging. A project manager's primary focus is to complete the project. However, it is important to recognize that much personnel development takes place within the project. Thus, a project manager has duties toward the care of individuals not previously recognized—for project appraisals and career development of staff (meshing with the duties of line management). HR can help here as well with training in the nontechnical skills needed and coaching on how to think about staff in terms of their professional development.

Staff development is of particular importance because this is one way for organizations to demonstrate commitment to their employees. Organizations are constantly evolving as they are impacted by numerous external and internal factors. The HR provides expertise in identifying and creating training and development programs to address the individual needs of staff and the organization and helps them manage change.

Project managers need to be comfortable managing conflict because, although sometimes disruptive, it can be both functional and helpful. The right level of conflict will

1. Bring change
2. Make team members more interconnected
3. Stimulate out-of-the-box thinking
4. Increase motivation

On the other hand, "inadequate or excessive levels of conflict will hinder the effectiveness of a group or organization, resulting in reduced satisfaction of group members, increased

absence and turnover rates, and eventually, lower productivity". Always seek HR when experiencing conflict. HR will listen, provide feedback, and pay attention to the details.

Managing performance issues is not simple and every organization has its own set of policies and procedures on how to address low performers. Involve HR as soon as possible because, if managed on time, HR can be a resource to the staff and help them correct performance. HR can also provide awareness of procedures should performance not improve, and advise on the next steps a project manager needs to take to avoid legal implications.

Summary

This chapter discussed different organizational structures and the importance of the system. These impact the project manager's role but options were discussed on how to leverage power, and the importance of making HR a strategic partner.

The following are the takeaways from this chapter:

- As a project manager, understand roles and responsibilities
  - Know the environment
  - Understand the boundaries
  - Feel comfortable in the role
  - Leverage the resources available
- Have fun working and managing people
  - They are your most important asset
  - Coach and nurture them

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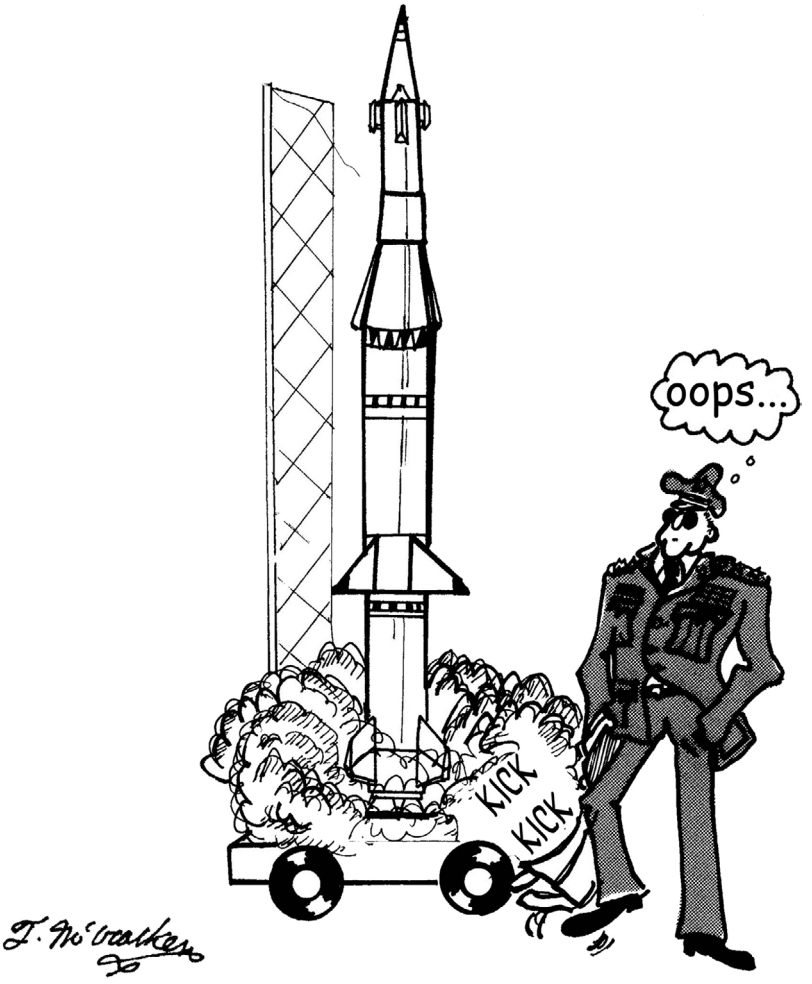
20

National Security Space

Marshal Ward

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Birth of National Security Space

The Space Age began as a race for security and prestige between two superpowers—the United States and the Soviet Union [1]. The event that set the stage for this race was the International Geophysical Year (IGY) that was planned to span the period July 1957–December 1958 and was intended to allow scientists from around the world to take part in a series of coordinated observations of various geophysical phenomena. The dates were selected to coincide with an approaching period of maximum solar activity. On July 29, 1955, President Dwight D. Eisenhower's press secretary, James C. Hagerty, announced that the United States intended to launch small Earth circling satellites between July 1957 and December 1958 as part of the United States' contribution to the International Geophysical Year. Four days later, Soviet scientist Leonid I. Sedov spoke to international reporters at the



FIGURE 20.1
Explorer 1 became the first satellite launched successfully by the United States when it was sent to space on January 31, 1958. A quick response to the Soviet Union's launch of Sputnik 1, Explorer 1's success marked the beginning of the U.S. Space Age. (Courtesy of NASA. https://www.nasa.gov/multimedia/imagegallery/. Accessed January 30, 2017.)

Soviet embassy and announced his country's intention to launch a satellite as well [2]. The space race was on.

Although the United States had planned to launch their satellite during the summer of 1957, they ran into technical difficulties and failed launches. The Soviet Union met its objective of launching before the United States with the launch of Sputnik 1 on October 4, 1957. The Soviets became the first to put an artificial Earth satellite into Earth's orbit. After several failed launches for the Vanguard program, Dr. Wernher von Braun was given permission to launch a satellite using a modified Jupiter-C rocket for the Explorer program. The United States achieved this goal only 4 months later with Explorer 1, on February 1, 1958. Since Sputnik 2 was successfully launched on November 3, 1957, the United States' Explorer 1 became the third artificial Earth satellite to be placed into orbit [2] (Figure 20.1). This was a large disappointment for the people of the United States. While Explorer was not the first satellite to orbit Earth, it was far more sophisticated than Sputnik and led to an interesting discovery about the space environment surrounding Earth. The instrument that flew on Explorer 1 was a Geiger–Muller tube with a micrometeorite detector and a cosmic ray experiment, designed by Dr. James Van Allen, which provided data and information that revealed regions of intense radiation surrounding Earth. These areas were named the Van Allen radiation belts after Dr. James Van Allen (Figure 20.2).

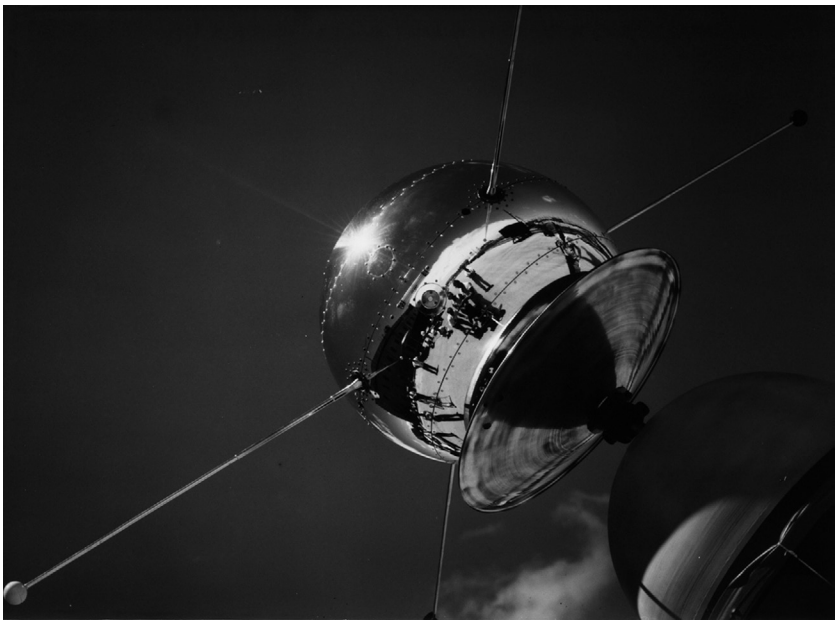


FIGURE 20.2
One of the Vanguard satellites is checked out at Cape Canaveral, Florida, in 1958. Vanguard 1, the world's first solar-powered satellite, was launched on St. Patrick's Day (March 17) 1958. It was designed to test the launch capabilities of a three-stage launch vehicle and the effects of the environment on a satellite and its systems in Earth orbit. Vanguard 1 was the second U.S. satellite in orbit, following Explorer 1, and remains the oldest artificial object orbiting Earth. Vanguard began as a program at the Naval Research Laboratory in Washington and was transferred over to NASA (along with many of its personnel) after the agency was founded by the National Aeronautics and Space Act of 1958. (Courtesy of NASA. https://www.nasa.gov/multimedia/imagegallery/. Accessed January 30, 2017.)

The launch of Sputnik 1 in 1957 shocked the United States and created a period of public fear and anxiety about the perceived technological gap between the United States and the Soviet Union and what the Soviet Union might do with their technology. The crisis was a key event in the early Cold War and caused President Eisenhower to create the Advanced Research Projects Agency, later renamed the Defense Advanced Research Agency (DARPA), to avoid future technology surprises. Also in 1958, President Eisenhower signed the National Aeronautics and Space Act, which became the first U.S. National Space Policy. The Act declared that the policy of the United States was to devote space activities to peaceful purposes for the benefit of all humankind. It also mandated separate civilian and national security space programs. This created the NASA to direct and control all U.S. space activities except those peculiar to or primarily associated with the development of weapon systems, military operations, or the defense of the United States (Figure 20.3). The Department of Defense (DOD) was to be responsible for these latter activities.

U.S. National Space Policy, June 28, 2010

Recognizing the boundless opportunities that have emerged since the first satellite was put into orbit several decades earlier and the radical transformation in daily life, to a great part



FIGURE 20.3
President John F. Kennedy and Dr. Wernher von Braun at NASA's Marshall Space Flight Center in 1962. (Courtesy of NASA/MSFC. https://www.nasa.gov/multimedia/imagegallery/. Accessed January 30, 2017.)

due to the use of space, the current U.S. national space policy has evolved to embrace five overarching principles that shape the national security space strategy:

1. It is the shared interest of all nations to act responsibly in space to help prevent mishaps, misperceptions, and mistrust. The United States considers the sustainability, stability, and free access to, and use of, space vital to its national interests. Space operations should be conducted in ways that emphasize openness and transparency to improve public awareness of the activities of government, and enable others to share in the benefits provided by the use of space.
2. A robust and competitive commercial space sector is vital to continued progress in space. The United States is committed to encouraging and facilitating the growth of a U.S. commercial space industry that supports the country's needs, is globally competitive, and advances U.S. leadership in the generation of new markets and innovation-driven entrepreneurship.
3. All nations have the right to explore and use space for peaceful purposes, and for the benefit of humanity, by international law. Consistent with this principle, "peaceful purposes" allows for space to be used for national and homeland security activities.
4. As established in international law, there shall be no national claims of sovereignty over outer space or any celestial bodies. The United States considers the space systems of all nations to have the rights of passage through, and conduct operations in, space without interference. Purposeful interference with space systems, including supporting infrastructure, will be considered an infringement of a nation's rights.

5. The United States will employ a variety of measures to help assure the use of space for all responsible parties, and, consistent with the inherent right of self-defense, deter others from interference and attack, defend our space systems and contribute to the defense of allied space systems, and, if deterrence fails, defeat efforts to attack them [1].

While the United States will use a whole-of-government approach to enforcing the U.S. national space policy, one particular space sector is identified in the U.S. national space policy as having the responsibility to execute this policy—that sector is the National Security Space sector.

National Security Space Sector

National Security Space is one of three distinct and interdependent sectors of the U.S. national space programs and capabilities. The other two areas are the Civil Space industry and the Commercial Space sector. The Civil and Commercial Space sectors are discussed further in subsequent chapters of this book; this section examines those aspects that fundamentally separate the three areas.

Each of the space sectors provides capabilities to meet the needs or desires of its unique set of customers or government sponsors.

Civil Space conducts activities that support

- NASA for space science, human and robotic space exploration, and space discovery missions
- The National Oceanic and Atmospheric Administration (NOAA) for environmental and earth observation and weather missions
- The United States Geological Survey (USGS) for land remote sensing mission

Commercial Space sector provides space goods and services or conducts activities through private sector enterprises. Commercial Space increasingly supports the civil and national security programs with innovation-driven entrepreneurship.

National Security Space conducts activities that support

- The Secretary of Defense and the Director of National Intelligence in meeting their joint responsibility to develop, acquire, and operate space systems to support U.S. national security and enable defense and intelligence operations during times of peace, crisis, and conflict.

National Security Space can be further broken down into its two subsectors: military space, and Intelligence Community (IC) space. Military space includes all space activities that support the responsibilities of the Secretary of Defense to

- Develop, acquire, operate, maintain, and modernize space situational awareness (SSA) capabilities. In this effort, the Secretary of Defense is supported by the Director of National Intelligence

- Develop capabilities, plans, and options to deter, defend against, and, if necessary, defeat efforts to interfere with or attack the United States or allied space systems
- Maintain the capabilities to execute the space support, force enhancement, space control, and force application missions
- Provide, as launch agent for both the defense and intelligence sectors, reliable, affordable, and timely space access for national security purposes

Intelligence Community (IC) space includes all activities that support the responsibilities of the Director of National Intelligence to

- Enhance foundational intelligence collection and analysis
- Develop obtain, and operate space capabilities to support strategic goals, intelligence priorities, and assigned tasks
- Provide robust, timely, and efficient collection, processing, analysis, and dissemination of information on foreign space and supporting information system activities
- Identify and characterize current and future threats to U.S. space missions for enabling adequate protection, deterrence, and defense
- Integrate all-source intelligence of foreign space capabilities and intentions with space surveillance information to produce enhanced intelligence products that support SSA [1]

Operating in Space

Space as a domain, has several unique characteristics that must be addressed when planning for operations:

- To date, there are no geographical boundaries in space. International law does not extend a nation's territorial sovereignty up to Earth orbit. Therefore, nations enjoy unimpeded satellite over flight of other nations in space.
- Movement in space is governed by orbital mechanics. Satellite orbits must follow certain orbital parameters due to the laws of physics. A satellite's orbit can be customized to best satisfy a satellite's mission. Once a satellite's orbit is selected, it is not usually changed because any change of orbit maneuvers can deplete propellant, which can significantly degrade the performance or life-span of a system.
- The space environment, itself, can be a significant limiting factor affecting the performance and life-span of any operational spacecraft. Apart from the threat of meteorites, almost many hazards to space capabilities come from the sun. The various phenomena resulting from the sun's activity are collectively termed "space weather" and manifest as increased radiation dosages, electromagnetic noise, ionospheric interference, or prolonged impact by energetic charged particles. Solar flares charged particles, cosmic rays, the Van Allen radiation belts, and other natural phenomena in space can affect communications, navigation accuracy, sensor performance, and even cause electronic failure.

- Operational satellites are under constant threat of impact by space debris. Space debris includes a myriad of phenomena including orbiting particulates left behind during a satellite's lifetime, debris from satellite explosion, or impacts, orbiting "trash" such as rocket bodies or natural objects such as meteoroids. Collisions with space debris can damage or utterly destroy space systems.
- Space-based assets depend on the electromagnetic spectrum (EMS) as their sole means for transmitting and receiving information and/or signals. The electromagnetic frequency bands that satellites use are fixed during development and cannot be changed after launch. It is vital that the U.S. forces achieve EMS control to ensure freedom of action for space assets [3].

Legal Considerations

National security space forces must comply with U.S. policy and laws, as well as U.S.-ratified treaties and international law when planning and conducting space operations. Today, there are relatively few restrictions on the use of space for military purposes. There has been much debate on "weaponizing" space and what exactly that means. The U.S. space doctrine acknowledges that the United States is committed to the exploration and use of outer space by all nations for peaceful purposes and the benefit of all humanity. Consistent with this principle, "peaceful purposes" has been interpreted to allow the use of U.S. defense and intelligence-related activities that are in pursuit of national interests.

The primary treaty that forms the basis of international law is the Outer Space Treaty, formally known as the Treaty on Principles Governing the Activities of States in the Exploration and use of Outer Space, including the Moon and Other Celestial Bodies. The Outer Space Treaty prohibits placing weapons of mass destruction in Earth orbit, installing them on the Moon or any other celestial body, or otherwise stationing them in outer space. It exclusively limits the use of the Moon and other celestial bodies to peaceful purposes and expressly bars their use for testing weapons of any kind, conducting military maneuvers, or establishing military-based installation and fortifications. However, the Treaty does not explicitly prohibit the placement of conventional weapons in orbit. The Treaty also states that the exploration of outer space shall be done to benefit all countries and shall be free for exploration and use by all the States. The treaty was signed in London, Moscow, and Washington, DC on January 27, 1967, and became effective on October 10, 1967. As of September 2015, 104 countries have become parties to the Treaty, while 24 others were in the process of having the treaty ratified by their governments [4].

What Is Outer Space?

Space, or outer space, is that void that exists between celestial bodies, including Earth. It is not empty, but consists of a vacuum containing a relatively low density of particles, predominantly a plasma of hydrogen and helium as well as electromagnetic radiation,

magnetic fields, neutrinos, dust, and cosmic rays. There is no firm visible or physical boundary where Earth's atmosphere ends and space begins. However, an altitude of 100 km (62 mi) above sea level, called the Karman line, is conventionally used as the start of outer space in space treaties and for aerospace recordkeeping. The Karman line is named after Theodore von Karman (1881–1963), a Hungarian-American engineer and physicist who was the first to calculate that around this altitude the atmosphere becomes too thin to support aeronautical flight [5].

Military Space Contributions to Joint Operations

Joint Publication 3-14, titled, Space Operations, provides joint (multiservice) doctrine for planning joint space operations. The guidance in Joint Publication 3-14 is authoritative and as such, this doctrine will be followed except when, in the judgment of the commander (combatant commander or other joint force commanders), exceptional circumstances dictate otherwise. The commander who has the responsibility to prioritize space capabilities and make apportionment and allocation recommendations on space assets for the DOD systems is the Commander, United States Strategic Command [3].

Planning Space Operations

When planning space operations, familiarity with these key planning considerations is essential:

- Global access—As mentioned earlier in this chapter, the fact that there are no geographical boundaries in space gives military forces global unencumbered access to all parts of the Earth from space.
- Orbit selection—There are many different types of orbits that can be used by space systems and selecting the best one for a mission depends on mission purpose. Orbits are usually classified by their altitude above Earth's surface. Low earth orbits (LEO) are located from 180 to 2000 km above the earth and are ideal for making the observation, for military purposes, and for collecting weather data. Geosynchronous orbits (GEO) are usually at an altitude greater than 36,000 km above the earth and have an orbital period that is the same as the Earth's rotational period of 24 hours. GEO orbits are used primarily by television, communications, and weather satellites. Medium-Earth orbits (MEO) exist between 2,000 and 36,000 km. This is where you will find the GPS navigation satellites. Each of the three types of orbits can be modified to some degree to accommodate a particular mission. While this description of orbits is rather fundamental, one should investigate these orbits and their variations in greater detail to understand how to get the most out of the physics that govern movement in space.

- Another important attribute of a satellite that must be considered in planning for a space operations mission is the design life of the satellite. Design life is dependent on how long the satellite must operate and function. Typically, the longer the design life, the more costly the satellite and in time, the more outdated the technology becomes.
- Space weather considerations are critical in planning a space mission. Unexpectedly large or frequent space weather events can shorten a satellite's expected life either by a significant single event, enhanced drag, or an increased rate of degradation to instruments and systems. As noted, the sun is a dominant source of space weather events and thus understanding solar cycles and what level of solar activity can be expected during a mission is another example of a critical mission planning activity.
- Satellite location predictability—A satellite's motion or orbital location is predictable, allowing for warning of satellite over flight, maintaining situational awareness, and tracking the location of objects in space. A satellite may maneuver and change its orbit making the orbit hard to predict, however, maneuvering may come at a high cost regarding onboard propellant.
- Vulnerability—All segments of a space system are vulnerable to interference or attack, and as satellite systems have become an integral part daily life, you must ensure your satellite system is there when you need it [3].

Space Missions Areas

Before January 6, 2009, joint space operations were organized into four mission areas: space force enhancement, space support, space control, and space force application. Underpinning each of these space mission areas was the need to have space situational awareness to execute the other four mission areas in a meaningful, efficient, and effective manner. On May 29, 2013, Joint Publication 3-14 was revised to realign space situational awareness as the fifth space mission area [3].

Space Situational Awareness [3]

> Space situational awareness (SSA) involves characterizing the space capabilities operating within the terrestrial environment and the space domain. SSA is dependent on integrating space surveillance, collection, and processing; environmental monitoring, processing, and analysis; status of U.S. and cooperative satellite systems; a collection of US and multinational space readiness; and analysis of the space domain. It also incorporates the use of intelligence sources to provide insight into adversary use of space capabilities and their threats to our space capabilities while in turn contributing to the joint force commander's ability to understand adversary intent.
>
> **U.S. Government Publishing (2016)**

Space Force Enhancement [3]

Space force enhancement operations increase joint force effectiveness by enhancing the combat potential of air, land, and sea forces, improving operational awareness, and providing critical joint force support. Space force enhancement is composed of ISR (intelligence, surveillance, and reconnaissance), missile warning, environmental monitoring, satellite communications (SATCOM), and PNT (position, navigation, and timing).

U.S. Government Publishing (2016)

Space Support [3]

The space support mission area includes the essential capabilities, functions, activities, and tasks necessary to operate and sustain all elements of space forces throughout the range of military operations. Components of space support include spacelift, satellite operations, and reconstitution of space forces.

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Space Control [3]

Space control supports freedom of action in space for friendly forces, and when necessary, defeats adversary efforts that interfere with or attack US or allied space systems and negates adversary space capabilities. It consists of offensive space control (OSC) and defensive space control (DSC). OSC activities are measures taken to prevent an adversary's hostile use of US/third-party space capabilities or offensive operations to negate an adversary's space capabilities used to interfere with or attack US/allied space systems. DSC activities are operations conducted to preserve the ability to exploit space capabilities via active and passive actions while protecting friendly space capabilities from attack, interference, or unintentional hazards.

U.S. Government Publishing (2016)

Space Force Application [3]

Space force application is combat operations in, through, and from space to influence the course and outcome of conflict by holding terrestrial targets at risk. The space force application area includes ballistic missile defense and force projection capabilities such as intercontinental ballistic missiles.

U.S. Government Publishing (2016)

The sum of these mission areas contributes to the safety, security, and stability of the nation they serve and to the international community as a whole.

How Space Systems Are Acquired by the Department of Defense

The DOD procures all goods and services from contractors, federal arsenals, and shipyards to support the military operation. Acquisition is a broad term that applies to more than just the purchase of an item or service. The acquisition process encompasses the design, engineering, construction, testing, deployment, sustainment, and disposal of weapons or related items purchased from a contractor.

As set forth by statute and regulations, from concept to deployment, a weapon system must go through a three-step process of identifying a required (needed) weapon system, establishing a budget, and acquiring the system. These three steps are organized as follows:

1. The Joint Capabilities Integration and Development System (JCIDS)—for identifying requirements
2. The Planning, Programming, Budgeting, and Execution System (PPBES)—for allocating resources and budgeting
3. The Defense Acquisition System (DAS)—for developing and/or buying the item

The Defense Acquisition System is an event-driven process that uses "milestones" to oversee and manage acquisition programs. At each milestone, a program must meet specific statutory and regulatory requirements before the program can proceed to the next phase of the acquisition process. There are three milestones:

1. Milestone A—decision to initiate technology maturation and risk reduction
2. Milestone B—decision to begin engineering and manufacturing development
3. Milestone C—decision to start production and deployment [6]

The JCIDS is a need-driven process and begins when an operational commander determines that the assets allocated to the commander are no longer adequate to accomplish the mission and meet the Strategic Guidance issued by the Secretary of Defense. That need (or requirement) must be validated by DOD's senior requirements validation authority, the Joint Requirements Oversight Council (JROC) before any funds can be expended on a new program. Once the requirement is validated, the DOD goes through a process to assess whether reallocating current systems or modifying a current system will meet the need. If the requirement remains unmet, then DOD conducts a Material Solution Analysis Phase to complete an Analysis of Alternative (AoA) to assess potential material solutions to capability need, identify key technologies and estimate life cycle costs. Commercial-off-the-shelf and solutions from both large and small business are considered and taken before the Defense Acquisition Board chaired by the Under Secretary of Defense for Acquisition, Technology, and Logistics for a decision to initiate a new program (Milestone A Decision) and enter the technology development phase. All programs are not treated the same. Major Defense Acquisition Programs (MDAPs) receive the most scrutiny by the DOD and the Congress. MDAPs are statutorily defined as DOD acquisition programs whose value based on FY 1990 dollars exceeds $300M of Research, Development, Test and Evaluation funding. Lesser dollar amount programs may have the decision authority for their program allocated to someone below the USD (AT&L) to allow for more expediency with major program decisions.

The Budgeting Process: Planning, Programming, Budgeting, and Execution System (PPBES) is an annual calendar-driven process that develops the DOD's proposed budget for all acquisitions, including MDAPs. The PPBES is intended to provide the DOD with the best mix of forces, equipment, manpower, and support within fiscal constraints. During the Planning stage of the PPBES, a national defense strategy is defined, and a plan is developed for executing the strategy.

The Defense Acquisition System is governed by the DOD Directive 5000.01, The Defense Acquisition System, and Instruction 5000.02, Operation of the Defense Acquisition System, and utilizes the procedures described in the Defense Acquisition Guidebook (DAG). The JCIDS is governed by the Chairman of the Joint Chiefs of Staff Instruction (CJCSI) and utilizes the procedures described in the Manual for the Operation of the Joint Capabilities Integration and Development System. The PPBES process is defined in the DOD Directive 7045.14. A working knowledge of these references is vital if involved in a DOD acquisition program [7].

Space programs have traditionally been major acquisition programs because of the high dollar value of the program. The DOD acquisition process has become very complicated and has not always produced systems that meet estimated cost or performance expectations. With the introduction of new enabling technologies for smaller satellites and hosted payloads, the cost for capability in space could decline dramatically.

Conclusion

During the past 55 years, the evolution of space has benefited the global economy, enhanced national security, strengthened international relationships, advanced scientific discovery, and improved our way of life. Today, the utilization of space has created new markets; helped save lives by warning of natural disasters; made agriculture and resource management more efficient and sustainable; enabled weather forecasting, GPS navigation, communications, and financial and banking operations; and has given humanity a deeper understanding and appreciation of our planet. Space activities began as a race between two superpowers, the United States and the Soviet Union; now there are more than 60 nations participating in space activities. Space has evolved to become a vital operational medium that rivals the operational mediums of the land, sea, and air. Space is the final frontier. It is the point of entry into our solar system, our galaxy, our universe. It holds the promise of a world where are all nations and all peoples can "live long and prosper." [8]

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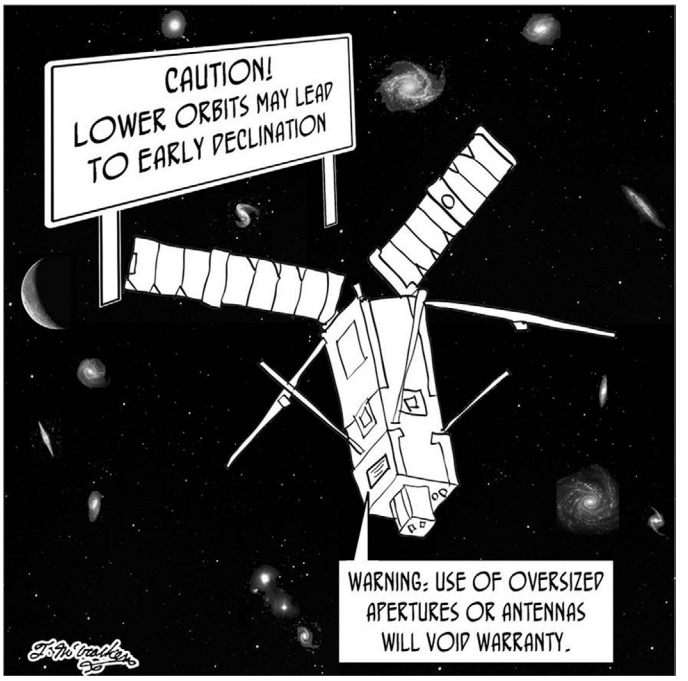
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Civilian Space Program Management

Glen Fountain

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What Is Civil Space?

Civil Space (as defined for this chapter) includes those enterprises that support the advancement in knowledge and technological capabilities that are government funded and are not part of the national security activities. The U.S. organizations that support civilian space are primarily the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS), with basic research support from the National Science Foundation (NSF). The goals of civil space are outlined by the "National Aeronautics and Space Act of 1958"* as amended (referred to in this chapter as the "Space Act"):

- The expansion of human knowledge of the Earth† and of phenomena in the atmosphere and space
- The improvement of the usefulness, performance, speed, safety, and efficiency of aeronautical and space vehicles
- The development and operation of vehicles capable of carrying instruments, equipment, supplies, and living organisms through space
- The establishment of long-range studies of the potential benefits to be gained from, the opportunities for, and the problems involved in the utilization of aeronautical and space activities for peaceful and scientific purposes.
- The making available to agencies directly concerned with national defense of discoveries that have military value or significance, and the furnishing by such agencies, to the civilian agency established to direct and control nonmilitary aeronautical and space activities, of information as to discoveries that have value of significance to that agency
- Cooperation by the United States with other nations and groups of nations in work done pursuant to this Act and in the peaceful application of the results, thereof
- The most effective utilization of the scientific and engineering resources of the United States, with close cooperation among all interested agencies of the United States in order to avoid unnecessary duplication of effort, facilities, and equipment
- The preservation of the United States preeminent position in aeronautics and space through research and technology development related to associated manufacturing processes‡

There are civil space programs in many countries other than the United States such as the European Space Agency. NASA's global partnerships are represented by more than 600 active agreements with over 120 nations from Argentina to the United Kingdom [1]. Support for participation by U.S. organizations is primarily through NASA (and in a few instances NOAA) agreements with funding primarily coming from these U.S. agencies (Figure 21.1).

The programs supported by NASA, NOAA, the USGS, and the NSF range from research grants as small as a few tens of thousands of dollars and months in duration to programs

* National Aeronautics and Space Act of 1958, Public Law #85-568 Stat., 26, signed by the President on July 29, 1958.

† "of the Earth" added in 1984.

‡ "The preservation … processes" added in 1988.



FIGURE 21.1
NASA, NOAA, NSF logos.

costing multiple billions of dollars and requiring decades to complete. The practices developed over the years by NASA and the organizations that support the civilian space enterprise have created a set of processes both in the realm of system engineering and program management to accomplish large complex tasks. These processes have been emulated to a greater or lesser extent throughout the world. In many developing countries one motivation for a space program is to develop a cadre of people capable of managing large engineering Programs to meet their societal needs.

As defined by the National Aeronautics and Space Act, civilian space focuses on the advancement of knowledge in Earth, and of phenomena in the atmosphere and space. In addition, civilian space focuses on the advancement in aeronautic and space technology. NASA's primary role is to advance the knowledge by developing new instrumentation, enabling spacecraft technologies, and the development of missions to gather cutting edge science. The National Oceanic and Atmospheric Administration (NOAA) is assigned the task of monitoring the Earth in the support of weather (and now climate) forecasting. The USGS provides scientific understanding of the natural hazards, the water, energy, minerals, and other natural resources essential to the modern world. Many of the techniques and instrumentation NOAA and the USGS use are often first developed by NASA to support basic research and as appropriate to use for long-term synoptic monitoring. The research of the National Science Foundation and the scientific community they support (in part) makes use of data supplied by NASA. All of these activities rely on management and system engineering techniques to create the instrumentation, vehicles, the technology, and the data that can be transformed into new knowledge that is a principal goal of the civilian space enterprise.

The civilian space enterprise is composed of many programs and projects. To successfully manage the programs and projects (often described as missions) their goals and requirements must be understood; these include programmatic, technical, and social requirements. Technical requirements begin as ideas about missions that can answer basic science questions and are often derived in detail over the course of the mission formulation and are discussed below as part of the process of acquiring a program or project. That is also true of the social aspects of the enterprise as the implementation of a mission requires the consensus of a variety of stakeholders be they research initiatives or flight missions. More formally, once a flight mission is established NASA designates it as either Class A, B, C, or D with each class defined in Table 21.1 [2]. NASA makes the distinction between programs and projects. In NASA parlance, a program defines a strategic direction

TABLE 21.1

Classes and Categories Translate into the Tolerance for Risk in the Project/Program Development Cycle

	Class C/D	Class B	Class A
Priority Level	**LCC* < $250M**	**$250M ≤ LCC ≤ $1B**	**LCC > $1B, Use of Nuclear Power Source, or Human Space Flight**
High	Category 2	Category 2	Category 1
Medium	Category 3	Category 2	Category 1
Low	Category 3	Category 2	Category 1

* Lifetime cost to complete.

that NASA has identified to implement an agency goal or objective (it may have multiple projects within the program). A project is a specific investment identified within a program plan having a beginning and an end [2]. For instance, the New Horizons mission to Pluto was a project within the New Frontiers Program. However, for consistency with the other chapters in this book, program will be used for both.

Table 21.1 differentiates different classes and categories that translate into the tolerance for risk in the project/program development cycle. The risk level at its most abstracted level focuses on a set of development items [3]:

- Single point failures
- Engineering model, prototype, and flight hardware qualification, acceptance, and prototype tests
- Reviews
- Adherence to safety level standards defined by NPD 8700.1
- Materials
- Mishap investigation board requirements
- Reliability
- Fault tree analysis probabilistic risk assessments maintainability
- Quality assurance
- Software
- Risk management
- Telemetry coverage

The approach to each of these development items depends on the category.

There are several discriminators between civilian space programs, and commercial and military space programs. First are the basic goals of these programs. The civilian space enterprise goals are defined by the Space Act. Commercial space programs include a profit goal in providing services through the use of space systems or supporting space systems. Military space is focused on the support of the government's national security and is supported through those government agencies associated with national security needs (the Department of Defense, National Reconnaissance Office, etc.). There are many differences in details that relate to the relationship between the program (and program management)

and the funding organization, but the primary distinction is on the public openness of the civilian space programs versus those of either commercial and military space programs. By their nature, the commercial and military space programs will closely guard the information about those programs for either competitive or national security reasons. By its very charter, NASA is to expand knowledge and although the Space Act identifies providing relevant national defense-related information to those U.S. agencies, the focus is on gaining and disseminating knowledge; and thus NASA has a more open policy of engaging the wider scientific and technology communities and the public at large on the results of their missions. There are two major limitations to this policy of openness: limitations to insure that information is deemed proprietary to the stakeholders (including information limited by the International Traffic in Arms Regulation [ITAR] or the Export Administration Regulations [EAR]) and the need for NASA (and its contractors) to speak with one voice. These limitations require the program manager to assure that the proper processes to meet these requirements are followed, but for civilian space there is a sense of openness in terms of communicating the results of tasks as opposed to a sense of limited communication for both commercial and military space programs.

Acquiring a Program

There are several paths to acquiring civilian space programs from a simple grant proposal to a long-term strategy to shape the environment and create a new program. This chapter focuses on larger programs that either respond to an existing program request for new ideas (often through an announcement of opportunity [4] (AO)) or a program that the civilian space agencies identifies as requiring the unique skills of an organization and directs that work to it on a sole source basis. In either case, the organization will lead the effort to shape the environment and in many cases acquire other partners to turn a potential opportunity into an actual program. This effort typically is an extension of the strategic planning of the organization. The program manager's role during the acquisition process is to assemble technical expertise to focus on a potential mission that the organization has identified and with that expertise develop a concept that can meet the general goals of that mission within constraints both technical and financial identified by the various civilian space stakeholders.

Understanding the Environment

Competition in the civilian space community exists in several areas: scientific or technical merit, technical capability, cost, and risk tolerance. Technical initiatives are often focused on a need to meet a significant national goal or a major scientific challenge. The science community raises many questions that can only be answered by instrumentation in space. The competition for which of these questions merit support is almost never clear-cut and requires consensus building within the community and within NASA as the funding agency for their execution. NASA often asks the National Academy of Science* (NAS) to lead the process of formally reaching consensus for major investigations through reviews that provide guidance over the following decade (Figure 21.2). The Congress also may weigh in based on the NAS reports and other

* The National Academy of Science was established to provide independent, objective advice to the nation on matters of science and technology by the Act of Congress in 1863.



FIGURE 21.2
Decadal survey covers.

input since they must appropriate the funds for major programs or, in the case of smaller projects, a portfolio of investigations with common general goals. The competition for implementing missions that pass the initial test of scientific merit must also pass the test of technical feasibility, cost, and risk level. NASA's risk tolerance varies with different administrations, but it is safe to say that it is never very high and thus for a mission to be accepted the scientific merit must be very high and the technical and cost risk very low.

In some cases, it may take years to prepare the foundation for major programs. For instance, the scientific questions that are being answered by NASA's Solar Probe Plus mission were raised at the beginning of the space age [5]. The idea for a mission to understand the sun's coronal heating and the solar wind acceleration processes evolved through many iterations within the scientific community, NASA, and their contractors before an approach was developed that could be accepted for development by NASA in 2011. To develop a credible mission many things had to happen: an improvement in understanding of the precise measurements needed to answer the fundamental questions posed by the science community, technological advances in instrumentation and materials, and innovation in system design that provided an implementation path that would meet budget constraints.

NASA uses the term "formulation" to designate this early phase of a program (through the preliminary design phase). It is usually used in a formal sense once a program has been created to develop a mission, and funding to support the completion of the concept, formalization of the requirements, and the preliminary design. But it can be thought of in the more general sense that includes all of the twists and turns that the "idea" of a mission

might take from the time the initial general science questions are asked until a mission concept has been developed whose implementation can answer those questions. During this early more informal phase, a program manager may be assigned by his or her organization to guide the discussion between the science community and an engineering team to create a concept, establish its technical feasibility, and develop a rough-order-of-magnitude (ROM) cost. In some cases, this leads directly into the more formal formulation process under NASA or other government funding. Depending on the circumstances, the general concept may move from one program manager to another and sometimes from one organization to another.

The discriminators for the duration of time spent in this informal state depend on the technical challenges and the agreement within the civilian space community with respect to the importance of the mission. As discussed earlier, some missions like Solar Probe Plus can take decades, but for others the path can be much shorter. In the 1970s, a number of missions moved from concept to implementation within a couple of years because the latent need for a set of measurements provided the impetus for quick development (this was the case for the MAGnetic survey SATtelite MAGSAT [6] developed in the late 1970s). The Near Earth Asteroid Rendezvous [7] (NEAR) mission went from early concepts to a funded mission in a few years in the 1990s because of the community need to support planetary investigations at a higher cadence than was the case during the 1980s.

Building a Team

During this early informal formulation period, the program manager must bring together a diverse set of team members: scientists, engineers, and technologists to identify the critical questions a mission concept is to answer; identify instrumentation that, if placed at the correct location, would make the measurements to answer the questions posed; and identify the space systems to place the instruments appropriately and return the data (and sometimes specimens) to Earth-based laboratories for analysis by the scientific community. To do this, the program manager needs to avail herself/himself of the widest knowledge base available to develop the critical questions (that help distinguish real from notional requirements) and develop potential concepts. This knowledge base will come from the manager's own experience and from senior members of the manager's organization. From this knowledge base a "core team" that will lead the concept development can be organized.

Each "core team" will be highly dependent on the focus of the mission, but there are some general rules that apply to the team's selection. First, the team members must be proficient in the general technical areas that they represent (e.g., scientist recognized for the discipline expertise, engineers and technologists from appropriate [to the mission general requirements] disciplines, and cost and schedule analysts to support the creation of an implementation plan). Secondly, they need to be able to work together as a team to be open to new ideas and to be able to balance the need for listening and discrimination as the initial conceptual ideas are winnowed down to a focused concept. The team members must also be able to recognize and articulate risks posed by the concept and identify plans for mitigation of those risks. The team members will also need to be accepting of criticism from both within and from stakeholders outside of the team.

As the concept moves forward from the early stages through the more formal formulation stage, this core team will be critical to success. The successful program manager will be careful in the selection of this core team, especially the system engineering team leads.

Coordination with the organization's management team to assure the identified team members are available and can properly focus on the concept development is essential. This is often a significant challenge as the more experienced staff desired for these roles will be in demand. Thus, getting buy-in from both the individuals and their supervisors is imperative. A major advantage in recruiting team members is the challenge and value civilian space missions often are seen to represent. It is one of the tasks for the program manager to properly frame those challenges and values as the team is formed to get each member's full engagement in the creative process that will result in a winning concept. For many civilian space missions, a science champion (often the principal investigator) will be a significant ally.

As a mission concept matures, the program team will be required to reach out beyond his/her organization to obtain all of the capabilities and services required to successfully implement highly complex technical endeavors that space missions often exemplify. In some cases, the scientific leadership may reside outside the home organization. In almost all cases, additional technical expertise, system elements, and services will be acquired from organizations beyond those within the home organization. The program manager and the program's core team will be critical in establishing the necessary relationships to key suppliers to assure tasks are understood and their execution is efficient. Early in the formulation stage, make/buy decisions are necessary, trading whether a technical element of the mission should be developed by the team or procured/subcontracted to a qualified external (to the mission) organization. Many can be made during the early informal formulation; but some may be part of the proposal and await trade studies performed early in the formal formulation phase. One example of this is the selection of a launch service provider. NASA often identifies several potential launch service providers but does not select one for a mission until late in the formulation period (and sometimes even later). This requires the program to carry alternate interface and environmental options into the detailed design phase. Other trades for subsystems may also be carried into the formal formulation phase but are usually resolved by the end of the preliminary design review milestone. Although formal arrangements may not be put in place at the onset of concept development, the general outlines of the relationships that will be formalized in contracts or other agreements need to be developed in the informal formulation state to assure that what is expected is well understood and that this understanding forms a sound basis for the contractual arrangements once the program moves into the formal formulation and implementations phases. The ability to extend the team to the larger group of organizations with well-understood agreements and a sense of common purpose is one of the critical skills of program management.

Developing a Proposal

Once an opportunity exists and a team has formed to pursue that opportunity, a well thought out proposal is required. In some instances, proposals are modest endeavors, but for most missions requiring significant expenditure of funds, NASA will rely on a competitive procurement (often through an announcement of opportunity) that will require a well thought out plan and a carefully written proposal. The core team, with support from the lead organization(s), must carefully define the rationale for the mission and its goals. This will require balancing science goals, technical feasibility, and cost. The overarching factor that NASA often uses in making a selection is the risk the proposed mission represents. NASA supports many missions and will want to limit the impact of a failure (or cost growth) of one mission relative to the other missions they support (their portfolio).

Thus, it is important that the proposing team be able to first frame the goals in a way that they can be accomplished while minimizing the technical and cost risk. Often in the development of the proposal, goals need to be reviewed as the concept proceeds to assure that the level of risk dose not grow in a way to make the final proposal non-competitive. The program manager has a key role in assuring that this difficult balance is maintained. Both the science team and the technical leads will desire to create the best scientific or technical mission possible, but such a mission may not be selected and it is a key role of the program manager to manage the desire to be the "best" so that it does not drive the proposal risk to levels that will not be acceptable.

Identifying mission goals provides the basis for detailed mission requirements development. The initial requirements based on the goals and the general mission concept are defined by the system engineering team with support of the program manager, the science team, and the cost and schedule analysis staff. The rigor of the requirements on mission systems will be an important determinant of the fidelity of the cost estimate derived and can be seen as a measure of the mission risk. Often the trades of system implementation (detailed science objectives, concept of operations, subsystem options, and details of instrumentation) based on minimizing cost and risk will be an important activity during proposal preparation.

A formal procurement will include a general list of deliverables to measure the success of the completed mission. The program manager will need to carefully review the list of required deliverables to the mission sponsor (generally in civilian space—NASA) to see that they are identified and costed in the proposal. Also the structure of the mission will require deliverables from the team members outside of the managing organization (who will be responsible to NASA for mission success) and the program manager and the core team will need to develop a plan that identifies those deliverables and to assure that they are properly documented in a way that when they become part of subcontracts no team member will be surprised.

The program manager is the key leader in identifying the tasks the team is to perform and the schedule that the completed tasks must meet—the program plan. During the proposal preparation, the tasks must be defined at a top level sufficient to prepare an initial cost estimate and the core team (and the organization) must agree to the tasks, the resources needed to perform the tasks, and the schedule for completion. Often there will be refinement of the requirements, tasks, and schedule to meet both cost and schedule constraints as the mission concept is refined during the proposal preparation. Throughout the process, the program manager will heavily rely on the mission system engineer and the scientific leadership to find the right balance of goals, schedule, and cost as defined by the program plan.

Cost estimation is a critical responsibility of the program manager. This topic is covered in Chapters 2 and 3 in more detail, but some general aspects are discussed here. Program managers rely on the organization's business office to supply the "official" cost estimates and the members of the organization staff that perform these functions are key to both a believable cost estimate and one that can be relied upon to assure the proper funding to successfully accomplish the mission's goals. Often several methods are used during the cost estimation process.

Early in the mission concept development, a "top-down" rough-order-of-magnitude (ROM) estimate will be developed by the program manager with support from the cost estimation staff. This will often rely on similarities to other missions and use past costs to determine if a given concept is within the range of acceptable costs for the mission opportunity. Two other methods are used to refine this initial ROM.

Once the concept is defined and a program plan is developed, the cost analysis staff can use models accepted in the industry to provide an estimate and the uncertainty in the estimate. This provides a method that allows the program manager and the organization to identify a price that includes the cost and a stated level of reserves as a means to mitigate cost risk. The other method is referred to as "bottoms-up" during which the technical team is asked to estimate the resources (staff time, materials, major subsystem procurement) to develop an independent cost estimate. The model-based cost estimate can then be compared to the bottoms-up estimate to see if there are significant differences. The program manager and the cost analysis staff can then resolve the differences either by making corrections in either estimate or by modifying the reserve posture to mitigate risks where significant differences remain after review.

Another aspect of the program manager's task during proposal development is to assure that the goals of the mission as stated can be met within the cost constraints. This key aspect requires both careful analysis and negotiating skills among the various team stakeholders. There is typically a desire to add capabilities to a mission by various team members and it is important to keep the key goals in minds. This helps to ensure that the team understands the risk of incorporating secondary goals and results in buy-in from the team in the compromises that are necessary to create a winning and successful proposal.

Balancing Programmatics, Technology, Engineering, and Quality

Proposed missions succeed when they balance scientific or technical goals within the confines of what is acceptable in terms of cost and risk. The program manager is key in leading this balancing act, but his or her most powerful tool in being successful is the wisdom of the team assembled to prepare the proposal and then to execute the mission. To access that wisdom the right questions need to be asked as the mission concepts are developed. Getting an initial concept that provides a solution to a particular set of mission goals is just the first step. With a concept in mind, the team must then ask those critical questions that allow trades to be made in terms of the cost, schedule, and technical ambition, and how each basic concept initially identified can be realized with appropriate quality and with acceptable risk. Closing this initial trade too quickly can lead to a proposal that is not competitive or cannot be realized within the programmatic constraints. By keeping these questions open, a "creative tension" arises that often helps to identify a solution space.

Closing the "Deal"

Developing a winning proposal requires more than an excellent concept; it requires a proposal that is able to succinctly communicate the ideas of the concept and provide sufficient data that will assure the selecting agency that the goals of the proposed mission can be achieved with low to modest risk. The level of risk acceptable to NASA varies with time and the NASA management team. There have been times where greater risk is acceptable than in other eras. The proposing organization and the program management must gage the current level of risk acceptance to both create a mission concept and then articulate that concept in the proposal that will meet that threshold of risk acceptance, and do so within limitations in proposal page count. This requires careful and creative ways to communicate both the value of the mission and the ability of the organization to successfully achieve the mission goals.

During the final phases of proposal development, the program manager must see that all the proper reviews and revisions are completed on very hard deadlines. At this stage, the program manager will need to work with the proposal staff to see that all edits are incorporated, all organizational approvals to submit the proposal are obtained, and that the proposal is delivered on time. As one former program manager stated, "My job was to do anything not done to get the proposal delivered."

Major proposals often require a site visit and a set of presentations that allow the reviewers to better assess the proposal. This is an opportunity to refine and expand on elements in the proposal that the page limitation made difficult. Between submitting the proposal and the site visit (or other means used by the proposal reviewers to solicit additional information) the program manager and the proposal team can start to build material to support the case where they believe that limitations in the proposal did not allow them to fully make their "case." Often the reviewers will generate a set of questions their initial reading of the proposal raises, which will give the proposal team a sense of potential weaknesses that they can concentrate on in their response. However, the time to respond to questions is generally very short and prior preparation is essential to complete proper responses in time.

Although a successful proposal is selected, a final step is required prior to execution, the negotiation of an actual contract that sets the binding parameters for the mission team's activities. The proposal will have a set of conditions, both technical and contractual, as part of the offer, but the limitations of the proposal process prior to selection limits the negotiation of details defined in the contract that must be settled before funds are transferred and the team can start. In many cases, some parameters that defined the boundary conditions created by NASA may change as part of the proposal acceptance. These may be minor or very significant. Minor issues are often quickly resolved, but some major changes may require the program manager to work with the organization management and the team to resolve before a final contract can be signed. For instance, the New Horizons proposed a launch date 13 months earlier than the date offered by NASA and directed that the project use a different radioisotope thermal-electric generator (RTG) than proposed. The New Horizons team was able to revise the program plan and determine that the modified plan was achievable within the offered parameters and acceptable risk.

Getting Started

Setting Team Expectations

The transition from proposal to development is a critical moment in the life cycle of a program. Although many of the team members have participated in the proposal, they may have been so only marginally. The start of actual development provides a milestone that can be used to get the team to really focus. It is at the "kick-off" meeting that the "potential mission" transforms into a very real task with both challenges and potential accomplishments. It is also an important time to communicate changes made to the plan based on the contract negotiations. Such a meeting allows the program manager to communicate expectations and it will begin to establish norms for the team as development proceeds. Although team members may be at various physical locations, they should be encouraged to come to a common location for this meeting (and from time to time over the course of the program to other critical meeting). There is great value in face-to-face meetings at such milestones. This allows the individuals to get a much better sense of each other and to develop a sense

of becoming a team with common purpose. This personal contact between the program manager and the team needs to continue throughout the development process. It will prove to be very valuable when challenges arise.

An element of a kick-off meeting is to provide information about the formal organization and when the formal channels of communication implied by the organization chart apply and when more informal communications among the team, which is critical, are acceptable. Typically, communication among the team is encouraged, but communications between the program and other organizations and especially the NASA sponsor need more formal control managed by the program office.

Another key item that requires formalization is the staffing plan. Prior to the completion of the contract, there are uncertainties in tasking details and schedule, yet the staff needs continued support. Thus, the final identification of staff and their transition to the program plan needs final approval by both the program and the line management. As part of this process any modifications to the schedule need to be incorporated into the master schedule and the associated work assignments.

Design Execution

Both requirements and implementation plans are often subjected to more formal review early in the design phase. There is a danger of "requirements creep" at this point. This is especially true if there is a change in the risk tolerance environment. The program manager must be alert to this type of change and be sure all parties—the team, the organization management, and the NASA sponsor—understand the implications of changes that are easy to accept at this point but will have significant consequences in maintaining the cost and schedule constraints set by the agreements made in the formal contract.

The system engineering team will define the series of reviews (the review ladder) as part of the system engineering plan that flows down requirements; then, the design and test reviews that assure the resulting system will meet those requirements; and, which system elements will require verification by analysis, test, or demonstration. The program manager will need to get early agreement on which of these reviews NASA will require their own staff to monitor and select review board members. It is usual practice for major programs that NASA will create an independent standing review board (SRB) to follow the program through the entire development phase. Although the major reviews can generally be identified as part of the program plan, not all will be. The overall program plan will need to be sufficiently robust (have sufficient schedule margin and cost reserves) to include additional reviews not foreseen at the start of the program.

Most missions strongly rely on the inheritance both as part of the mission design and at the subsystem/component level. Care must be taken that the assumptions implicit in the inherited design be fully understood and those assumptions are compatible with the planned mission—their "fitness for use." The program manager and the system assurance (quality) manager should see that the initial design assumptions are appropriate as part of the program review process.

Subcontract management is a key part of the early design phase. Often a major schedule driver will be the delivery of system components. There is a natural tension between having all of the design details in place and initiating a contract that will provide for the timely delivery of key components. These items should be identified as part of the proposal, but if they are not, agreement with all stakeholders needs to be reached on the timing of these contracts in the design phase (often being required to start prior to design completion as measured by a system critical design review). The program manager needs to carefully

monitor the development of all contracts, but be especially mindful when early fabrication is initiated due to schedule constraints that the design has properly matured such that the risk of later changes is minimized.

Often there are design options that require analysis as part of the preliminary design when sufficient detail is available (detailed requirements identified, environments defined, subcontractors selected that affect design details, etc.). It is highly desirable to complete these design trades prior to the preliminary design review. Trades carried beyond that milestone represent significant threats to both cost and schedule. For the New Horizons mission, two launch service options were carried well into the detail design phase at some additional cost. The risk of such delays need to be carefully analyzed by the program manager and communicated to the key stakeholders.

Fabrication, Integration, and Test

Transforming designs into a functioning system is the most critical element in the program's life cycle. It is at this point that weaknesses in the design or failure to sufficiently plan the logistics of fabrication can create serious schedule delays and/or cost growth. This is also part of the development cycle during which the staffing is at its highest level and thus the sensitivity of cost growth to schedule delay is greatest.

In some cases, the delays may be driven by events outside the direct control of the program such as failure of a vendor to meet performance or schedule requirements. Another source of delay can come from a failure on another program of a system element or component that is critical to the mission design. There are times when the failure of a vendor to meet the program schedule results in the need to find an alternate source. Careful monitoring by both the staff delegated to monitor the vendor subcontract and the program manager is required to identify such risks early and develop a mitigation plan.

The program manager typically relies on the system assurance manager to monitor subsystem and part vendors to assure that the delivered item will meet the "fitness for use" quality requirement. In some cases, a problem results in a difficult choice. For example, in the early 2000s the integrity of a widely used class of field programmable gate arrays (FPGAs) came into question. Some devices were reported to have failed after being programmed. The failure seemed to be correlated with certain manufacturers; yet the probability of failure appeared to be extremely low and potentially related to a programming process. The Mars Reconnaissance Orbiter chose to change out all devices from one manufacture shortly before launch. The New Horizons mission chose not to change out similar devices believing the risk of making the change outweighed the part failure risk. Both missions successfully achieved their mission objectives. The program manager is required to make these difficult decisions, but he or she needs to rely on knowledgeable program staff for relevant technical information and to see that key stakeholders are informed of the issue early and brought into the decision process.

It is a rare mission development during which some fabrication or test problem does not arise. The program manager needs to have staff, tools, and options at her or his disposal to identify these problems as early as possible, take quick action to understand them, and take appropriate remedial action. It is important to remind the team to be on the lookout for issues and to report them to the program manager as soon as they arise. It is also incumbent on the manager to be their own best communication link by personally inspecting (by "walking around") the fabrication and test sites and talking to team members where they work. Even the most competent staff will have a tendency to solve the problem at their

level and may not formally report an issue in its early stage. Even if it is proper to leave the issue at the lowest level for solution, the program manager should be informed and by "walking around" he/she can get an early assessment and prepare to take action to mitigate any risk arising from the problem.

It is also during this period where the close working relationship established during the design phase between the program management and the development team members can result in communication that addresses problems in their early stages and allows the type of collaboration that identifies a solution minimizing their potential impact. This sense of teamwork produces a momentum of its own that allows even very serious problems to be taken in stride and solved.

Close communication with the stakeholders, those within the program team, the sponsoring agency, and the organization within which the program is being developed is essential to success. Communication of technical, schedule, and cost performance minimizes the surprises that can damage relationships and impede success. It also allows these various stakeholders to support the program as the need arises for resources that may not have been foreseen during the program formulation. This is particularly true when problems arise and alternative plans must be executed to resolve the problem.

As development ends and the test and verification process is in its final stages, the program manager will be called upon to communicate (usually through reviews, but also with formal data packages) the results to the stakeholders within his/her organization and to the sponsor at an ever more frequent cadence. These stakeholders will want sufficient information to make their own assessment of the technical, schedule, and cost performance especially as the delivery/launch date approaches and the ability to use schedule delays to solve problems comes at great cost. These assessments will also allow the sponsor and organization management to perform their own due diligence and affirm that the mission elements delivered by the program will meet with success when delivered to a higher level of integration or launched. Many of these reviews and data deliveries will be identified during the program planning stage, but some will arise in response to development problems and their resolution. The program manager will need to have sufficient resources to respond to both the planned and unplanned sponsor requests. Most importantly he or she must keep the challenges in perspective, the team moving forward, and provide information with a clear assessment of the status that includes the remaining risks to success.

Launch Campaigns

Space missions are unique in that they are exposed to a great (perhaps the greatest) risk after the hardware (be it an instrument, subsystem, or spacecraft) is designed, fabricated, integrated, and tested. This is due to the criticality of launching the system into space. The launch milestone induces a significant environment and risk of failure to place the spacecraft on the correct trajectory. Launch failure rates vary from 2% (Tsyklon 2/Delta II that have long histories that allow improved reliability) to nearly 50% for systems that are relatively new and with a median probability of failure of 14% for some 45 launch systems as tracked in the reference [8]. The program manager has modest control over the launch vehicle performance as his choice will be limited by technical and sponsor-imposed constraints, but he/she can make important contributions at the margins. The first is to assure that the best launch service within the mission constraints is chosen. More directly, the program manager can assure that interfaces to the launch service provider work well and

that requirements (launch trajectory, spacecraft environments during ground operations, etc.) are understood as the design process is completed. As the spacecraft integration and testing draws to a close, the focus must turn to the coordination of final preparations of the spacecraft for launch and to assure that the mission operations team is ready to operate the spacecraft once launched.

Choices of launch vehicle and launch services in civilian space are limited by those made available by the government (NASA in particular). In many cases, only one or two service providers are possible, but within those constraints the program manager and the mission team need to support the government team to be sure that all mission requirements are understood and the selected vehicle will meet those requirements.

Developing a good relationship with the launch service provider at multiple levels on both sides of the mission/service provider interface is a key enabler to having success. There will be many details of the interfaces that will involve many technical contributors. The program manager and the launch service provider management must work closely together to see that their technical teams have as open and clear a communications path as possible. This recognizes that some elements of the launch services may involve proprietary information that the program team will need to carefully control. Failure to do so may limit the communication of critical information that could lead to failure.

The preparation for flight operations began with the mission concept and is matured during the course of development. The mission operations maturity (hardware, software, and team training) is part of the flight readiness assessment. It is another aspect of the mission that the program manager must coordinate. The mission operations manager is part of the core team established at the start of development and is someone whose leadership is another key to success. Establishing communications between the launch site and the mission operations center is the joint responsibility of the program manager, mission system engineer, and the mission operations manager. The communication requirements include the network between mission operations and the spacecraft to assure continuous evaluation of spacecraft health during launch and early flight operations. Also, clear communication among the mission operations team and the mission team at the launch site is essential if a problem arises during launch and early operations when key technical team members are separated and some contingency action would be needed to mitigate such a problem.

The launch of a spacecraft is one of the key milestones in a mission life cycle (the other being successful collection and return of the data, which is the reason for the mission itself). Given the risks involved and the payoff of a successful launch, the entire team will be in a heightened state of anxiety. The program manager needs to be mindful of the team's state of mind and be prepared to move them to action if a contingency response is needed or to acknowledge their key contributions upon a successful outcome.

Operations and Results

Planning for the operational phase starts with the concept of mission operations that were part of the initial mission concept and then flowed down into the requirements for the ground system hardware, the ground system software, mission operations staffing and training, and the management of data (both mission health and safety and science). It is desirable to have all of these elements in place at launch, but having all completed is the exception rather than the rule for most civilian space missions. The program manager needs to distinguish between those elements that are critical to be in place and those that can be (or in some cases best be) delayed until flight operations began. This separation is

especially valuable for planetary mission where there are often long periods between development, launch, and arrival at the target destination.

Unlike the overall program staffing that peaks during integration and test and then declines to a significantly smaller number at launch, the mission operations staff must be sustained for a very significant period of time (sometimes for over a decade). Managing this staffing profile has challenges of its own. For long duration missions, the ability to delay some tasks into the mission operations phase is of great value. The primary value is that it allows the operations staff to first hone and then maintain skills over the long period during which the spacecraft is in flight and the flight activities are few. Long duration missions also require that the program manager and the organization management work together to maintain staff stability. Staff stability is key to successful mission operations and yet the needs of individual staff to advance in their own careers are competing demands and the successful management team will find ways to help career advancement while maintaining a stable staff.

Flight operations bring their own set of risks. In flight, the means of assessing the health of the spacecraft and responding to problems when they arise are limited. Prior to launch, the mission operations and the mission system engineering teams will have thought through potential faults due to either spacecraft failures or human error. Some of these potential faults will have a first line of defense in the design of on-board autonomous fault protection. Others will be developed as part of the mission operations contingency operations planning. One of the program manager's roles is to set the tone in terms of risk management and therefore to what depth the risk and subsequent mitigation panning will be carried. During development, the acceptable risk tolerance may be at a moderate level (a few percent probability of occurrence and low to moderate levels of impact). This allows the team to focus on mitigating the really serious threats to success. The more unlikely risks need only be addressed if they occur, since recovery on the ground is possible. Once in flight, however, recovery is much more difficult and thus a lower tolerance of flight risks is likely. Prudent management suggests that even very remote risks should be considered and appropriate contingency plans made.

Civilian space missions are often focused on the return of scientific data. This data is to be shared with the general science community and thus must be prepared in a timely manner for delivery to the appropriate NASA data center. An example is the planetary data system* where data from NASA's Solar System Exploration missions are archived. Links to other archives for disciplines such as Heliophysics, Universe Exploration, and others can be found at the NASA Space Science Data Coordinated Archive website (http://nssdc.gsfc.nasa.gov). For a NASA mission to be successful, the science data must be archived in the appropriate data center. Guidelines for archiving, which includes repository, data format, and review process, can be found on the NASA Planetary Data System (PDS) website. Plans and the appropriate archiving tools will need to be prepared in advance of data collection as the science team will be pressed to both evaluate the science data as it arrives on the ground, publish science results, and deliver the data to the PDS.

Civilian Space missions are a community affair. They not only involve the mission team, but the wider science community and the public (who pays for them). Space science missions begin with the support of the wider science community through the national academy review process and this community gets a chance to participate through their access to the science data and collaboration with the science members of the mission team. Thus, timely delivery of the data products and reports to the community at science meetings and

* Information on the Planetary Data System can be found at https://pds.nasa.gov.

publications are an essential part of the mission life cycle. These missions also provide an opportunity for the public at large to get insight into the mission. As part of the planning, a public outreach (or public engagement) program element allows the public to share in the excitement of space exploration. The coordination of such programs with NASA is essential. As the sponsoring agency, NASA takes great care that the civilian space missions are seen as part of their "brand" and the management of information from the team to the public will need to be well coordinated. The program manager will be one of the key communicators in this process. Coordination with NASA and among the team will assure that the "image" presented to the public is consistent and that the ability to share the excitement enabled. Public interest and access is a two-edged sword; it shares the excitement and helps to maintain the public's support of the civilian space program; however, the intensity of that excitement can sometimes be overwhelming if the proper plans are not in place at appropriate milestones such as launch and during a planetary encounter. With modern media, another aspect of the excitement is the potential for cyberattacks, which could be hidden in the extremely large web traffic that some events generate. The New Horizons mission had some 1.7 billion web "hits" during the Pluto encounter. To mitigate any cyber security risk, the New Horizons website was moved off the mission operations campus. Yet, the final result of such intense interest is a major plus for NASA, the community at large, and for the mission team!

Ending in the "Black"

It is often said that the task is not complete until the "paper work" is finished. But the "paper work" is just the documentation for the record of a more important aspect of the mission life cycle and program manager's responsibility. That more important task is to assure that the "promises" made at the start of the mission have been met in the eyes of NASA (or other sponsoring agency), the organization management, and of the team itself. Closure for each group will be of great value to future activities and a source of satisfaction to all.

Sponsor satisfaction has both a formal and informal aspect. The formal aspect is completed when the deliverables under the contract have been transmitted and acknowledged as complete by the agency. But, in addition, it is what the sponsor thinks about the mission as it ends that is equally valuable. And that often includes a number of different individuals who have various roles within the government who will see the program in light of their own responsibility. The program manager's role here is to identify those stakeholders and gain insight on their views. If one or more of these stakeholders believes that some aspect of the mission has not been completed satisfactorily, it is important to understand that position and to determine if that concern can be remedied. At a minimum, differences in opinion about outcomes should be understood and fed back to the program manager's organization as part of the mission lesson learned activity.

The program manager's organization is another important stakeholder whose opinion of the mission's success is critical. The organization will have their own set of expectations and measures of success that must be addressed. Did the program enhance or put at risk the organization's reputation? Were the financial expectations of the organization met? What lessons learned will be of value to new and other ongoing programs? Getting answers to these questions, communicating them to the organization's management, and resolving any open issues provides closure for the organization and the program manager.

A most important element of program closure is assessing the team's performance, identifying lessons learned for future use, and recognizing the creativity and hard work of the team.

For missions that are successful and for those that encounter severe problems (including failure), it is essential that lessons be learned and the team's work acknowledged. The success rate of civilian space missions usually means that this will be a time for celebration and that the lessons learned are seen as leading to improved performance in future endeavors. It is on those occasions during which a major problem occurs that the program manager is called upon to rise to the challenge of bringing the team together to assess what occurred and why it happened, and to support the team through a time of high emotions as they work through a time of intense stress. In all cases, it is important to recognize the team's efforts and to see that they feel that their dedication to the mission had value.

Civilian space is an exciting enterprise. It has great challenges and rewards for program managers. The challenges come from pushing the envelope of technology, science, and exploration that require complex systems and a diversified set of contributors. Mastery of these challenges and contributing to the success of the enterprise provides great satisfaction in a program manager's career.

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Managing Small Projects

Edward L. Reynolds

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Overview

For many organizations, their bread-and-butter projects are large in size and scope. Their processes and tools are optimized to efficiently work with these larger projects. But as shown in this chapter, organizations also need to be able to concurrently implement small projects for a variety of reasons. These smaller projects do not quite fit into the mechanics of the organization and must adapt to work. This chapter delves into the challenges of small projects and their benefits, and ways to work within the construct of an organization created for larger projects.

Small Projects: Part of a Well-Balanced Portfolio

Small projects are part of every healthy organization. They allow organizations to change and adapt. They are critical for developing new products and technologies. They allow organizations to create their secret sauce that makes them unique in the marketplace. Organizations need a portfolio of projects of different sizes to sustain themselves.

Small projects are a mechanism for change. Successful organizations change with the times and adapt. For the same reason IBM does not sell punch card readers any more, over time organizations have transformed themselves to offer entirely new products to their customers. Organizations that fail to adapt or create new opportunities perish. They must adapt to new technology and develop new capabilities through innovative designs. Some also change their organizational structures and the processes they use to perform. Most of this change is implemented through projects. Some of these changes are small and easy to incorporate into an existing system. But dramatic change is risky and needs to be tested at a smaller level.

Small projects allow new ideas to incubate to form new technologies while accepting a level of risk that is unacceptable to large programs. Many organizations use internal research and development (IRAD) projects to mature an idea into something useful to the organization. Many IRAD projects are very small and consist of one or two people working alone and thus do not typically require the framework of a project. But other IRAD projects require interaction among multiple groups, and have deliverables, and do fall into the definition of a small project. Once a new technology is developed, it must be validated before full-scale incorporation into the organization's larger projects. Again, small projects serve as the proving ground. Small projects can be pilot programs and occasions for technology demonstration where a new technology or change in process is first tested with little investment and risk to the organization. For an aerospace organization that makes spacecraft costing almost a billion dollars, a small CubeSat project performs a valuable service in maturing and validating new technologies and achieving necessary flight heritage before risking larger missions (Figure 22.1).

Small projects represent an opportunity for organizations to take risks that larger projects cannot. With these risks comes the possibility of high reward. As with the IRAD projects mentioned earlier, many of these projects will not lead to something useful to the organization. In a sense, the project was a failure. But that's okay. The costs were small. The larger projects were not put at risk. And, ideally, the organization did learn something from the endeavor. In pursuing breakthrough and change using small projects, the organization develops a healthy tolerance to failures.

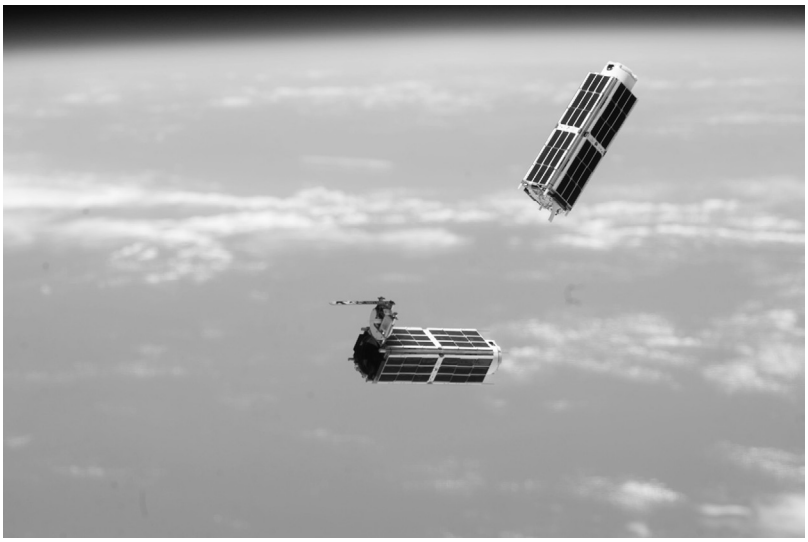


FIGURE 22.1
NanoRacks deployed from a space station. A set of NanoRacks CubeSats is photographed by an Expedition 38 crew member after the deployment by the small satellite orbital deployer (SSOD). The CubeSats program contains a variety of experiments such as earth observations and advanced electronics testing. (Courtesy of NASA Image Library. https://www.nasa.gov/multimedia/imagegallery/index.html. Accessed January 30, 2017.)

Small projects represent an excellent training ground for new and early career employees. As discussed later, much of the framework of the small projects is the same as the larger projects; small projects expose new employees to the critical pieces of the organization's project environment and lifecycle at a scale suitable for learning. These small projects also allow new employees the opportunities to take control and experience project decision making without risking the larger projects and the organization's reputation.

A key challenge of small projects within large organizations is to overcome the impedance mismatch of the desires of the small project team with the ingrained processes, culture, and values of the large organization, which to date have proven successful. Small projects try to be agile but operate in an environment of methodical gate reviews and strong configuration control and change control. Small projects are more accepting of risk but operate in an environment that is risk-averse. Small projects want to exploit the resources of the organization but often lapse into organizational inertia where the organization does not know how to deal with something different from a large project. Finally, a small project is often defined as the lowest priority within the organization, and is bumped in its queue in terms of resource availability.

There are benefits to small projects as well. Their small size means that communication is greatly simplified and team members can often collocate into one work space. Meetings can be spontaneous since key stakeholders are present. Documentation can be reduced and a simplified system of configuration management and change control can be invoked.

It is important to realize that small projects depend on the same concepts of planning, execution, control, and monitoring needed for larger projects. The trick is to recognize and adapt to the challenges of working within a larger organization while exploiting the benefits of a small project team. An effective approach to achieving this is to streamline the project.

Framework of a Small Project

Much of the framework used to organize successful small projects is the same as that used for large projects, but streamlined. Small projects tend to have a small core team that stays together through the project's lifecycle. It is important to assemble that core group as early as possible to identify the project's goal and objectives and then develop a plan to achieve those objectives. Starting early achieves buy-in and commitment from the staff, which will ultimately perform the work. The members of the core team need to recognize that the small project environment is slightly different from the normal project environment. The core team needs members who are flexible but who recognize boundaries of project management. Projects that work outside of a management framework are not projects; they are just people spending the organization's money without a plan or a definition of success.

Early on, the core team should brainstorm how the project will work. Given that small projects need to be a part of the larger organization's portfolio, there should be a history of previous small projects from which to learn. Some accepted small project processes may already be in place. If not, they should be organized. The core team needs to have several individuals who are seasoned in the workflow of the existing project environment. Team members should gather and discuss how the project will operate:

- How have previous small projects been implemented in the past?
- What pitfalls exist in the current organization that your small project should try to avoid?
- Will the project team members have to interact with others outside the core group? Example: fabrication shops.
- What level of quality is required? What level will the organization accept?
- What organization tools are too cumbersome? Example: earned value management.
- How will you measure project performance?
- What work should be performed in-house and what is best procured or subcontracted?

Many answers to this "how" will reside in your small project's plan. The project plan identifies the classic project management approach (organization, cost, work breakdown structure, schedule, constraints, risk management, configuration management, communication, documentation, parts and materials plan, change control, gate reviews, etc.), but also defines the caveats and exceptions to be put into place that will allow the project to operate more nimbly within the framework. Once written, project plans need the approval and buy-in of the organization. It is important to obtain formal approval of the streamlined approaches that the team envisions to define the working environment of the project.

Below the project plan are the small project's subplans. They are simplified, one- or two-page versions of plans used for larger projects. Many small projects will try to get by without these plans but will find that work will become stalled within the organization without clearly defined direction; the staff in a high-quality organization is trained to follow processes, and when normal processes aren't followed, work stops (Figure 22.2).

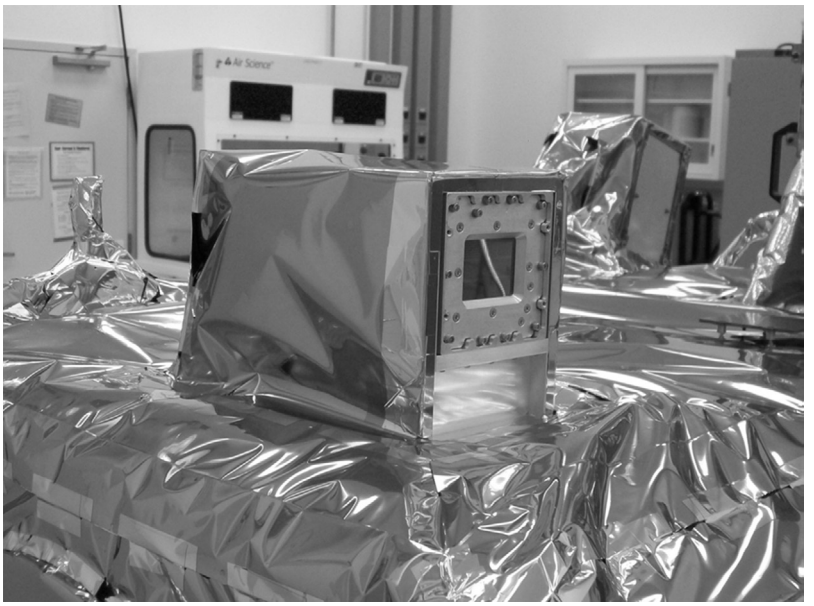


FIGURE 22.2
Canary-mounted instrument for the Space Test Program—Houston 3—Canary (STP-H3-Canary). The US Air Force Academy and the Johns Hopkins Applied Physics Laboratory instrument investigated the interaction of ions with the background plasma environment around the International Space Station, March 2011–September 2013. (Courtesy of JHUAPL, Image Library, Laurel, MD.)

Project Initiation

Projects, especially small ones, are initiated in many different ways. Some organizations have committees that formally evaluate a small project concept against a strategic roadmap. Sometimes small projects are initiated at the whim of a single individual. Sometimes they are built around sufficiently innovative or interesting ideas that the organization simply decides to proceed with. While small projects are meant to be aggressive in the amount of risk they are willing to tolerate, the overall cost–benefit rationale needs to make sense. For example, does it make sense for an organization that builds spacecraft costing hundreds of millions of dollars to invest significant IRAD funds in developing CubeSats spacecraft that can be purchased commercially for less than one million dollars? On the face of it, the economics just doesn't work even if it is successful; however, all advantageous aspects need to be considered, such as validating new technology that can feed larger programs or quickly building a cadre of experienced staff. Like larger projects, small projects do need to undergo a litmus test to determine whether the reward is worth the risk and the investment. Badly conceived projects that succeed technically can be strategic failures and represent lost opportunities elsewhere.

Regardless of how a project is initiated, it is critical to identify the goal of the project among the project stakeholders. This seems obvious but examples exist of projects in which after months of work the three key stakeholders could not agree on whether the project was about weather forecasting, new scientific discovery, or investigating a fundamental

question about cloud formation. Each was working in isolation and giving conflicting information to the engineering team. It is critical to sit down and collectively agree about what is broken that needs fixing.

The project plan should also define the scope of the project from the very beginning. Since the projects are small, they don't get a lot of attention from management and different stakeholders will make different assumptions about what the final deliverables are and what defines the success of the project.

The project plan should address the level of risk and the types of risk the organization is willing to take in its execution. It should also identify who ultimately owns the risk and will accept risk when it is identified and not mitigate it. While many small projects can accept higher levels of risk, they still need to fully assess the consequences if the risk is realized and then make decisions about whether the risk is worth the reward. Within the core group, the project manager is the decision maker about whether to avoid risks, mitigate risks, watch risks, or accept risks but accepted risks do need to be communicated to all stakeholders, especially the organization and the sponsor paying for the work. If a risk is realized, there must be collective knowledge of its possibility before it occurs.

Once initiation is complete and planning is ready to proceed, a kick-off meeting with the key stakeholders is in order so that everyone understands the marching orders and also sees that the organization is notified of the concepts of the streamlined approach. If the small project is large enough, it may make sense to physically collocate the core team members together to enhance informal communication through the team.

Small Project Planning

Just as with larger projects, planning a small project starts with a good project plan and work breakdown structure (WBS). The level of detail in the WBS can vary depending on how it is to be used. At a minimum, it should be product-oriented. WBS titles should be nouns and should reflect the product item in its successfully completed state. If an item is to be procured, the WBS decomposition can stop at that item name. Items that are built in-house should be decomposed further. The WBS should focus on the objectives and their deliverables, which should all align with the scope defined in the project plan. Along with the WBS there should be a WBS dictionary. Many times the WBS will have just a couple of words like "ground system," which is meant to cover a significant fraction of the project's scope. The dictionary will define what is meant by these two words and if they include significant items like the mission operations center, or the integration and test equipment. As planning progresses, the WBS and its associated WBS dictionary serve as the foundation for developing the project schedule and cost plan. During the planning process, all three items are living documents that are changeable, as long as they remain self-consistent with each other.

Microsoft Project (MSProject) remains the *de facto* tool of choice for project planning. The project manager should learn this planning tool to the point of populating resource-loaded schedules. Small projects may want to consider developing a truly resource-loaded schedule in which people and equipment are planned into the schedule tasks. Given the limited number of people within a small project, the scheduling of people and equipment to tasks and the prioritization of those tasks can be critical. Another benefit of the resource-loaded schedule is that costs can be assigned to tasks and rolled up within the WBS structure. This cost-monitoring approach would be unofficial and would not replace the

organization's approved accounting system, but its implementation can provide more intimate insight into the project's costs and project performance.

Task work within the project schedule should be structured consistently with the WBS and should capture the scope and deliverables that are documented in the project plan. The level of detail in the schedule network should focus on achievements that can typically be made over a period of time on the scale of a week. Complicated interaction may require planning in finer detail.

When planning the project, the team should have an awareness of the perceived priority of the project within the organization. A low-priority project may find itself at the back of the queue when it needs to use the organization's designers or fabrication facilities, as the larger projects demand immediate attention. For these parts of the schedule where work is performed outside the core team, significant slack needs to be planned into the schedule. If this is not possible, then the project manager will need to use their influence within the organization.

During the development of the schedule, the project manager and the team should pause and review it. They should assess it for risks and pitfalls and for ways in which the project can exploit the resources of the larger organization in a streamlined manner. The project manager should identify the limited documentation that will record decisions and agreements (interfaces) and how this documentation will be controlled, whether within the group or using the organization's formal systems.

Small Project Execution, Monitoring, and Control

The project team should try to execute to schedule. Work items that depend on resources outside the core team should receive priority to eliminate them as a source of risk. In a colocated work environment, team communications are essentially continuous. There is still the need to meet regularly and assess how development is proceeding versus where it needs to be. A regular meeting at the beginning of each week works well to assess the status of the schedule and communicate issues. Such a meeting can have an informal atmosphere but should be conducted against an agenda of topics including open action items.

A well-running team will have developed good cohesion, and setting goals for the week works well. Working according to the schedule as a team, the group should identify where they need to be at the end of the week in terms of completed tasks. The team should have some latitude to optimize their activities as a group to meet the weekly goals. Not everything needs to be within the schedule and worked according to the schedule plan. The schedule plan is a tool to be exploited by the team. It needs to change when necessary within allowable program constraints.

With smaller projects, the need for adherence to a detailed schedule baseline is reduced. A project can establish milestones, such as design reviews, and manage their schedule against those references.

Mission assurance: The quality of the small project's deliverables depends on the expectations of the sponsor, the end user, and the implementing organization. The project manager needs to interact with each of these stakeholders early and establish an understanding of those expectations. For projects that deliver a product outside the organization, there may be a minimum threshold of quality requirements that the organization imposes to protect the organization's reputation.

Effective mission assurance keeps the project honest. At times, this effort to review progress to date and address issues that have occurred along the way may feel like an impediment to finishing the project, but it helps assure that unnecessarily risky shortcuts are not being taken. Small projects need a balance of working nimbly without the overbearing presence of constant monitoring and justification with the need to interact with mission assurance when needed. One way to do this is to implement anomaly reporting (AR). During the building and testing of a deliverable item, anomaly reporting should be in place. Anything unexpected or unusual generates an entry into the AR system. The small project's system assurance manager (SAM) interacts with the project team in addressing and closing these ARs. It forces the team to step back and look at the cause of the problem. Ideally, the SAM and team will get to the root cause of the anomaly quickly.

Measuring performance: Measuring the performance of small projects is not the same as with the larger projects. Larger projects involve considerable work and resources to implement systematic performance-reporting tools such as certified earned value management (see Chapter 4). These processes require a critical mass of planning and baseline plan review and validation that small projects cannot afford. For small projects, a different approach is needed. One approach is to analyze the small project schedule and identifying objective accomplishments, such as the approval of a specification or a completion of a design review that can be scored against a milestone baseline. During the project planning phase, small projects should try to identify a hundred or so milestones in their schedules that can establish a baseline milestone profile and a cumulative milestone profile. As the project progresses, the project manager scores milestones accomplished against the baseline profile.

Another method is to implement a lightweight earned value management system within the MSProject. To do so the schedule tasks should be loaded with allocated costs, which is something that MSProject supports. As tasks are completed, work is reported as earned in dollars. Earned work is compared with the actual cost to perform that effort. Such an approach depends on the ability to accurately estimate the cost of work. It also depends on the organization's accounting system's ability to accurately charge work against specific tasks.

During the building phase, the count of ARs generated and closed should be reported as a performance metric. The generation of ARs is not a negative indicator; it is the recognition of the team's sensitivity that something is not right. It is the generation of ARs coupled with the closure of ARs that is the real measure of a project under control. The lack of closure of ARs, as recognized by the accumulation of open ARs, indicates that the team is not focused on quality (Figure 22.3).

Pitfalls of Small Projects

Luck is not a strategy: Small projects are at a disadvantage in most organizations. Usually larger projects receive priority in resources and attention. This adds to the level of risk that small projects experience in addition to the usual risks. Practicing risk management is critically important to the success of small projects. Small projects should recognize the challenge to resources and organizational priority, plan significant slack into schedules, and proactively seek to accomplish tasks as early as possible.

Cutting corners: Small projects can enjoy nimbleness. They can do things quickly that larger projects, with their established processes, cannot do. Part of the nimbleness is due



FIGURE 22.3
Sounding rockets are often used to conduct multiple small experiments at an apogee around 99 km. Typical Wallops Flight Facility launch with student participants. (Courtesy of NASA Image Library. https://www.nasa.gov/multimedia/imagegallery/index.html. Accessed January 30, 2017.)

to the limited scope of the project and the limited number of stakeholders involved. Part of the nimbleness can also be from the small project's decision to not do things expected of the larger projects, such as requirement reviews, design reviews, risk management, configuration management, change control, and prototyping. Given the small size of the project, the organization may not notice excessive cutting of corners. Small projects can proceed a long way through their lifecycle with no significant issues arising. Many times it looks like the small project approach is a new paradigm for managing projects. This is what happened in the 1990s when "faster–better–cheaper" was the mantra. After early successes such as the Near Earth Asteroid Rendezvous (NEAR) mission, imposition of additional process requirements complicated the ability of streamlined programs to operate, resulting in an increase in the desire to cut corners to achieve goals. It was during acceptance testing of missions, and after launch, that the consequence of excessive streamlining was noticeable. Project managers should interact with the organization at the start of the project and agree on what can be throttled back with little risk. Working with the organization assures the project manager that the organization understands the risks and stands behind the project's approach.

Limited oversight and review: As stated earlier, larger projects are the focus of management. Given the limited time available for management, smaller projects don't receive frequent and regular attention that larger projects "enjoy." Management may not know about emerging issues of the small project, unless the project manager has a conduit to a representative in management. Likewise, when it is time to conduct reviews, finding good reviewers who are not overburdened with the large projects can be a challenge.

Overly aggressive risk posture: It is an accepted belief that smaller projects can accept more risk than larger ones. In general, this is true, but may not be universally true. It is important to understand who owns the risk and how much their willingness is to accept risk. Depending on the project, some sponsors may be just as risk-averse as with large projects. For projects where the stakeholders are willing to accept more risk, this is not a license to

be reckless. Risk that is accepted should be accompanied with substantial benefit. When a risk is taken and accepted, this action by the project manager must be communicated to the sponsor and the implementing organization. In the end, the project manager manages the risk, but it is the sponsor and the implementing organization that suffer some consequences if the risk is realized.

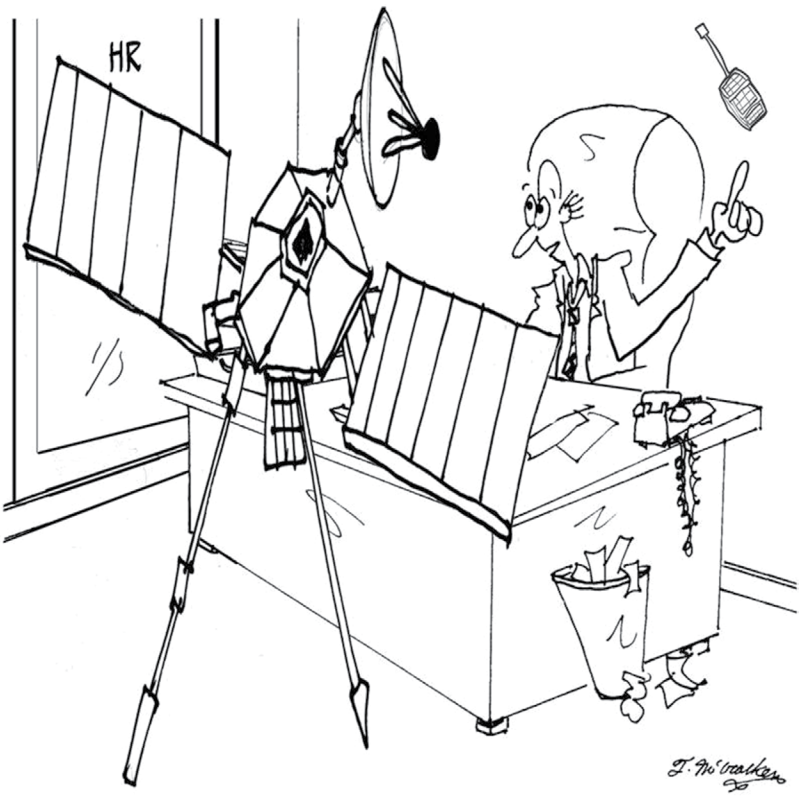
Poor equipment: Most of a project's cost is labor. Many times the procurements represent a small fraction of the project costs. Buying or building extra hardware can add flexibility to the project when things don't go according to plan.

Teaching bad habits: New employees may view the small project environment as the normal project environment. This may result in a higher acceptance of risk that they bring to their larger projects.

Avoiding the learning curve: Many projects will define a small core group and then try to perform all the work within that group. This can eat into precious budget while having team members learn a specialized new skill. If the objective of the small project is not meant to be a learning experience, then work should be delegated piecemeal to skilled people, especially in a matrix-managed organization where the project manager can buy several hours of skilled labor to perform specialized tasks.

Section V

Aerospace Project Management Emerging Topics



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The Changing World of Space Program and Project Management

Earl R. White

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Introduction

The job of the program manager (PM) hasn't changed much in the seven decades of satellite systems development. Technologies have improved, but design and acquisition have been driven by the realities of the satellite industry: high cost of launch, a hostile space environment, and the inability to modify a satellite once placed into space. This leads to expensive, capable satellites with a high probability of surviving the expected length of the mission. PM may be concerned with cost and schedule, but they are dominated by performance.

What does the future hold for the space PM? Nils Bohr famously quipped, "Prediction is very difficult, especially if it's about the future," but it is clear that tomorrow's space professional will face a very different world than those of the preceding decades. There are changes afoot, driven by new technologies, innovative business practices, and evolving national strategies.

The Harvard Business School uses a century old case study to illustrate a fundamental principle of organizations particularly relevant to the space enterprise. At the close of the nineteenth century, the U.S. Navy was considered one of the most modern and effective of any naval force in the world. They had successfully made the transition to steel hulls and steam turbines, and proven their effectiveness with dramatic victories over Spanish fleets in the Spanish–American War. If gun accuracy was poor—on the order of 2% of shots fired actually hit their intended targets—it was as good as or better than any other naval service. Into this environment, an inventive British Admiral developed a new method of sighting naval guns that resulted in a 3000% increase in hit rates. Admiral Percy Scott introduced a new hand-cranked elevation gear and a telescopic sight, allowing his gunners to use the roll of the ship to adjust gun elevation, with dramatic results. These innovations were witnessed by a young American naval officer, Lieutenant William Sims, who attempted to have the same improvements incorporated into the U.S. Navy. The Navy's bureaucracy, however, proved enormously resistant to these modest changes, first ignoring, then disputing, and finally insulting Sims, despite evidence that was indisputable. Sims eventually ignored his chain of command and wrote directly to the former Secretary of the Navy, then President Teddy Roosevelt, who immediately recognized the value and importance of this new technique. President Roosevelt intervened, appointing Sims to be the Navy's lead for incorporating continuous aim gunnery across the fleet.

This case study illustrates what Harvard Business School professor Michael Tushman calls the Tyranny of Success. Stated succinctly, successful enterprises are organized and rewarded to support current practices, and the institutions are resistant to change. The more successful the organization, the greater the internal resistance. For these successful enterprises, transformational change normally requires a significant outside stimulus.

Traditional satellite manufacturers and operators of commercial, civil, military, and intelligence space systems have been enormously successful over the last decades, and are today demonstrating the Tyranny of Success. Absent an outside stimulus, institutional inertia favors small numbers of large, expensive, long-lived and uniquely designed space systems, using well-established principles of program management, while slowly adopting new technologies. Traditional space, however, is today experiencing not just one transformation-inducing stimulus, but three.

The first major stimulus is a dramatically changing threat environment. Having recognized the advantage the U.S. military gains from the use of space, and realizing the vulnerability of existing military and intelligence community satellites, some nations are investing

enormous resources into the development of counter-space weapons. Space will no longer be a sanctuary, and this will impact not just the military, but all space users.

The second major stimulus comes out of Silicon Valley. Today's PMs will witness a transformation in the way some satellite systems are built and operated, and will be forced to live in the "clash of cultures" between traditional satellite acquisitions and operations and the so-called NewSpace practices coming out of Palo Alto, Seattle, Denver, Boston, and other technology hubs around the world [1]. NewSpace takes advantage of existing technologies and in some cases works on the leading edge of technology development, but is primarily a set of business practices. It promises significant advantage, particularly for national security space users concerned with resilience in the face of conflict. More significantly to the PM, though, NewSpace business practices will likely drive changes to the entire space industry, affecting every aspect of space acquisitions and operations. Professionals trained in traditional program management techniques will find they need new and sometimes very different skillsets to work effectively with NewSpace.

The third major change is technology driven. Developments in space robotics and automation have opened up the possibility of servicing, repairing, and modifying satellites while in space. While DARPA is investing in relevant technologies, commercial space enterprises are looking favorably at the economics of commercially funded life extension missions. The United States is only one of many countries investing in satellite servicing. Success will change the economic calculus driving satellite design and operations, and fundamentally change the overall role of the PM.

Brief History of Space Warfare

The idea of a conflict in space is not new. The United States and the former Soviet Union began designing and building anti-satellite (ASAT) weapons only a few years after Sputnik. The first operational ASAT weapons were nuclear tipped missiles fielded in the 1960s. The United States built and tested a conventional air-launched direct ascent ASAT missile in 1985 before cancelling the program in 1987 out of concerns for debris production and political concerns over ASAT proliferation. The Soviet Union fielded an orbital ASAT system in the 1980s. In their book "Anti-Satellite Weapons, Deterrence and Sino American Space Relations" Michael Krepon and Julia Thompson list 53 known U.S. and Soviet ASAT tests between 1960 and 1984 [2]. The USSR's ALMAZ military space stations even carried a 23 mm rapid fire cannon to defend against perceived U.S. ASATs! [3]. Defensively, the United States hardened the most critical satellites to the effects of a nuclear explosion in space. Even given the resources and planning going into space combat, however, the barriers for the use of counter-space weapons were very high. Both superpowers knew the other's red-lines, and short of a full-scale nuclear war, space was safe from military conflict. This cold war competition came to an end with the fall of the Soviet Union in 1991, and the world enjoyed a brief period where space was indeed a sanctuary.

Today's threat of conflict in space is very different from the earlier period, and has its roots in a U.S. cold war strategy known as the Second Offset. The term "offset" refers to a way of countering the strength of potential adversary without having to match that strength—essentially the development of asymmetric warfare. The First Offset Strategy introduced tactical nuclear weapons into Europe to deal with the Soviet Union's numerical superiority in main battle tanks. The Second Offset Strategy introduced stealth and

precision maneuver warfare through the development of an integrated GPS network and the integration of large numbers of intelligence surveillance and reconnaissance (ISR) sensors, some from space. The implementation of this new strategy came to be called the AirLand Battle, and the first major test occurred in 1991.

The 1991 Gulf War was labeled by the Secretary of Defense and many others as "the first space war" because of the essential support provided by space systems [4]. The world was watching as the United States and its allies destroyed the world's fourth largest army in 100 hours. Russia and China, in particular, were alarmed at the effectiveness of this strategy against forces modeled after those of the Soviet Union, and began investigating new military strategies of their own. Russia made little immediate progress due to the collapse of the Soviet Union, but China began an offset program of their own known as the "Assassin's Mace," intended to develop asymmetrical weapons and doctrines to counter U.S. strengths. In Chinese folklore, an assassin wielding a mace was able to defeat a much stronger enemy, leading to the name. China began developing weapons to negate America's advantages in precision warfare and advantages in the aircraft carrier battle groups seen as a regional threat to mainland China. Counter-space weapons were seen as key components to both. In 2007, China successfully tested a version of a ground launched direct ascent ASAT missile, destroying an aging weather satellite and producing a great deal of debris, to international condemnation. Today, both Russia and China have well-funded, comprehensive counter-space development programs, and many other nations invest in the GPS and Satcom jamming systems available on the open market. In a reaction to these foreign developments, the United States in 2015 dramatically increased its investment in space defense amid talk of a Third Offset Strategy. This new strategy invests in deep learning systems, wearable electronics, autonomous systems, and adaptive systems, and involves close collaboration between the Department of Defense and Silicon Valley. One of the more visible manifestations of the Third Offset Strategy is the Defense Innovation Unit, experimental (DIUx), set up at Ames Research Center in Sunnyvale, California in 2015, and expanded in 2016 to include branches in Cambridge, Massachusetts, and Austin, Texas [5]. Although the DIUx was initially directed toward the big data developers of Silicon Valley, Secretary of Defense Ash Carter later included commercial space. The DoD is intentionally seeking to leverage the space entrepreneurs of Silicon Valley, Seattle, Denver, Boston, and other tech centers, and that will involve exploring new ways of acquiring and using space systems. Reviews are mixed as of this writing, but there is a clear understanding by both DoD and Silicon Valley that DoD acquisitions needs to change. As one company CEO said, "We have no problem with the Defense Innovation Unit-Experimental, we have no problem with all of the innovation and mission owners. We have a serious, serious problem with the contracting officers and the purchasing process [6]." If successful, DIUx could be the impetus for a much-needed acquisition reform that could affect the PM's working directly for DoD and the commercial companies that support national security space.

Space as a Military Area of Operations

The most significant difference between the space warfare environment of the cold war and that faced by the space professionals of the near future is a dramatically different barrier to use. Cold war weapons, many armed with nuclear warheads because of the difficulty of directly striking their targets, were designed to be used only in the event of a

nuclear engagement between the superpowers. It was made clear to the Soviet Union that an attack on the U.S. missile warning or assured communications satellites would be regarded as the first shots of a nuclear war. The Gulf War, however, demonstrated how strategic space systems had become tactically significant and thus considered by some as fair game in a conventional conflict. The weapons in development or operations today are conventional, precise, and capable of threatening satellites in every orbital regime. Satcom jamming, and to a lesser extent GPS jamming, have become commonplace across the world. Demonstrating the ability and will to deny, degrade, or destroy a high value national security satellite is viewed by some as a low-risk means of strategic deterrence in a geopolitical conflict.

For the PM working civil or commercial space systems, the potential for space conflict might seem to be irrelevant to their work. Unfortunately, this is not the case. The rise of counterspace threats will influence the space PM in several ways. Space is a new warfighting domain. The rules of space warfighting are yet to be written and there is an uncertainty how different actors might conduct themselves that affects all of space. Will civil or commercial systems need to worry about debris producing weapons? Is an adversary willing to interfere with GPS regionally or system-wide? While there is uncertainty over the full range of attacks that would be directed against satellite services, there is no doubt about two kinds of attacks, because they occur on a fairly regular basis. Comsats will experience ground-based jamming, and cyber-attacks will be directed against ground and space-based components of space systems. For more than a few nations today, downlink jamming is a preferred method of attack against offending satellite signals.

During the cold war nonmilitary satellite builders could afford to ignore threats, as a nuclear war would present far bigger problems to the company than malfunctioning satellites. In tomorrow's more limited conflicts, however, specific commercial and civil satellites could be at considerable risk. Any satellite seen as supporting one of the belligerents, for instance, may also be seen as a fair target. Military use of commercial Satcom, while economically attractive for a company, can place a large asset at risk. The same can be said for commercial imaging satellites. Currently, the most likely form of attack on a Comsat is from uplink or downlink jamming, which can be mitigated by the advanced beam forming and signal processing techniques coming into use today. A PM will have to stay aware of the developing threats and possible mitigations as the space domain enters the measures and countermeasures cycle familiar to the air, land, and sea combat environments.

Another threat to space comes from the possibility of increased debris in important orbital regimes. Despite the international outcry from China's debris producing ASAT test, China has continued with the development of kinetic-kill space weapons, likely seeing them as cheaper and more assured than other less technically mature attack mechanisms. In LEO orbits, debris from hypervelocity impacts spreads over time and increases the risk of collision to other satellites that are in that orbit or that pass through that orbit.

A satellite owner must also consider operations in a GPS-denied environment. While most GPS denial attacks will originate from inexpensive local jammers, there are also regional and global-scale attack mechanisms that could deny the GPS signals used by satellites for onboard position and timing. A wise PM will examine how well the system can continue to operate in a GPS-denied environment, and determine if a backup is warranted.

The most immediate threat, however, comes from increasing developments in cyber warfare. Cyber has become the frontline for the preparation of the battlespace, through exfiltrating key information and the planting of malware. Any technical PM has to be aware of cyber threats, but for the space PM some of the threats are coming from the

intelligence and defense organizations of nation states. Civil, commercial, and DoD space systems share common components, and there are national resources behind some efforts to compromise those components. Today it would be wise for every space PM to be competent in cyber security. Tomorrow it will likely be a necessity.

In the face of ASAT weapons development, organizations supporting national security space are looking to build more resilient space architectures. While a great deal of money is being invested in protecting existing systems, organizations are also looking at smaller and cheaper satellites in cross-linked constellations, and are putting more attention to hosted payloads. The jury is still out on the space architectures of tomorrow. The director of the National Reconnaissance Office has said she believes the existing systems can be made survivable [7]. Air Force Space Command is examining disaggregating the strategic missions from the tactical missions, diversifying missions, leveraging smaller spacecraft buses, and considering hosted payloads early in the acquisition process. For the space PM supporting national security, this is a time of dynamic change. For the PM in the commercial and civil worlds, national security space just might be coming to them for solutions.

Significance of NewSpace

The last decade has seen startling changes in the commercial space industry, driven by a new generation of space entrepreneurs, supported by a positive regulatory environment and an investment environment bullish on space, and inheriting technical developments from research in small, micro, and nanosatellites. These changes follow the classic pattern of a "disruptive innovation," first defined by Harvard professor Dr. Clayton Christensen. In his words, "Disruption describes a process whereby a smaller company with fewer resources is able to successfully challenge established incumbent businesses. Specifically, as incumbents focus on improving their products and services for their most demanding customers, they exceed the needs of some segments and ignore the needs of others." He goes on to explain that disruptive companies gain a foothold by targeting the low end, underserved segments with cheaper solutions, and then gradually move upmarket, taking over market share from traditional companies. NewSpace is doing just that, growing to fill the lower-end markets for communications and remote sensing by using advantages in cost and speed of development. If the pattern holds true, NewSpace will evolve to compete with traditional space markets, to include national security space. There are many indicators to suggest this is precisely what is occurring.

The term "alt space," or "alternative space" came into vogue in the 1980s to describe commercial space companies attempting to develop suborbital and orbital launch systems separately from NASA and the Air Force. In the mid-2000s the term was supplanted by "NewSpace," and expanded to include the entrepreneurial companies developing satellite services by leveraging new small sat and CubeSat technologies. There is no formally accepted definition of NewSpace. It includes the new commercial launch companies, satellite builders and operators, and companies building support systems and user applications. The ecosystem is diverse, but there are some characteristics common to many of the companies including themselves in the term.

NewSpace companies are founded by entrepreneurs. Some are skilled technologists coming out of NASA and traditional satellite companies with a vision to use existing technologies to fill business gaps. Some are businessmen who see the possibility of getting in

on the ground floor of a major new industry. NewSpace companies are well funded by Venture Capitalists (VC) and Angel investors, or by one of the several technology billionaires interested in space. Angel investors are often high net worth individuals who are willing to risk capital for higher returns to help a small company grow into the next phase of investment where they may exit and be replaced by debt or equity investment. They and the VCs are driven by the promise of large returns on investment—expecting on the order of a 20× rate of return—looking to reprise the profitable investments in wireless communications of the 1980s. The Tauri Research Group estimates that VCs have invested between 1.5 and 2 billion dollars into NewSpace companies in 2105 alone, with one new company being funded every month. Angel investment has grown by more than 300% in less than 4 years. A quick web search identifies over 24 new commercial satellite constellations being proposed, funded, or in some stage of development with satellites ranging from 1U Cubesats to 175 kg smallsats and totaling over 10,000 satellites! The technology billionaires differ from the venture capitalists in that they bring not just investment dollars, but their own visions of the future that shape developments of today. Elon Musk, for example, wants to colonize Mars, and builds technologies to support his vision.

Another enabling change was the rise of the CubeSat. Although some NewSpace companies are developing very capable satellites in the 50–150 kg range, it is the many variations on the 10 cm × 10 cm × 10 cm CubeSat bus that opened the doors to very low-cost commercial missions. When first developed by Stanford and CalPoly in the late 1990s, CubeSat were inexpensive platforms that matched the budgets of academia and were considered by many as little more than toys. The next decade saw the involvement of government funded labs, Federally Funded Research and Development Centers (FFRDCs) such as the Aerospace Corporation, and University Affiliated Research Centers (UARCs) such as Johns Hopkins University Applied Physics Lab and the Utah State Space Dynamics Lab. Satellite buses matured and many higher end sensors and spacecraft components were miniaturized to fit the buses. By 2013 a majority of CubeSat launches were nonacademic [8]. NewSpace companies utilizing CubeSat are characterized by very fast development timelines using agile techniques pioneered by Silicon Valley software companies. Some commercial CubeSat have been built in garages, and in one case a startup built their vacuum chamber from parts found in a junkyard. Timelines for developing new satellite models are measured in weeks and months. Hardware modularity promotes the reuse of engineering and manufacturing much like software reuse was enabled by web services, resulting in lower component reliability but higher systems reliability. Interface control becomes more important than requirements documents. A NewSpace PM or project manager (PjM) must be skilled in scrum techniques for the software portion of the mission, and expert in small team dynamics discussed in Chapter 24. Many small startups have very few managers, so each is given a great deal of responsibility. As the industry matures and begins to increasingly mix with government and traditional satellite developers, the NewSpace PM will also need to be skilled in the traditional PM techniques. Even more, there will probably be an increasing demand for PM's who can bring both worlds together.

To date, NewSpace has built almost exclusively for Low Earth Orbit (LEO). This relatively benign radiation environment combined with the short expected lifetimes of the satellites allows for the use of nonradiation hardened parts. The short expected mission lifetimes are considered a plus to this industry, allowing frequent replacements and maintaining current technologies. Satellites are built with the most current processors instead of the older and more expensive rad-hardened and space qualified processors of traditional space, allowing them to take advantage of Moore's Law. CubeSat designs often include the latest cell phone chips and electronics from the automobile industry. As parts of the

industry look beyond LEO, companies are turning to the additive manufacturing industry for 3-D printing of radiation shielding.

Because of the low cost of satellite development and launch, the CubeSat end of the industry seems to shun modeling and simulation in favor of on-orbit testing. As one industry CEO explained it, "the best simulation environment for space is space." For the PM, this means more attention to cost and schedule, and less on reliability. The implication of this, however, is that since failure is an option, the PM will have to plan for surviving mistakes.

Many NewSpace startups seem to operate less like satellite companies than like big data companies developing new sources of information. As more satellites are launched, new companies are formed to develop the applications to turn observations into services. Many of the applications are merely commercial versions of what the intelligence community has been doing for decades. Some, however, leverage the emerging, unique strength of NewSpace—that of persistence. The ability to proliferate sensors, even if low resolution compared with their traditional space brethren, brings something entirely new to earth observation—the ability to monitor every place on the earth with sufficient temporal, frequency, and spatial resolution to measure activity on the scale of an individual. The vision of the founder of one commercial imaging company is for anyone with a smartphone to be able to get a new one meter resolution image of anywhere in the world within 90 minutes for approximately $100. The proliferation of electrooptical (EO), multispectral, hyperspectral, and imaging radar sensors will bring an unprecedented transparency to the world. Anyone with a smartphone and credit card will have access to this extraordinary network of earth observing satellites.

LEO Comsat Mega-Constellations

As much as NewSpace earth-observation promises (and threatens!) to change the world, it is actually satellite communications that dominates this business. A 2014 study by the well-respected technical futurist firm Reperi LLC indicates that "more than 80% of underlying future satellite demand will come from broadband; 17% from imaging, and the remaining 3% from a host of other satellite sensing data." NewSpace Comsat companies dream of an economical "internet in the sky," without the time latency that comes from relaying signals to geosynchronous satellites. The new companies are moving to much lower orbits and proposing huge constellations. As of this writing, there is one constellation already at Medium Earth Orbit (MEO), two large LEO constellations in the design and manufacturing phase, and one in proposal. O3b—the "Other Three billion"—has a full constellation of 12 satellites at 8062 km to balance latency reduction with size of the constellation and was recently acquired by satellite operator SES. OneWeb plans to fly 648 satellites at 1200 km orbits to provide global internet broadband by 2019. OneWeb's Ku band license is already approved, and the company contracted with Airbus Defense and Space to manufacture the satellites. SpaceX is planning a 4000 satellite constellation at 680 km orbits, all cross-linked. The satellites are to be mass produced at a new factory in Seattle, with the hope of providing global wideband internet coverage by 2020. Samsung has proposed a 4600 satellite constellation at 900 km. Boeing has recently asked for licensing of up to 2956 V band satellites at 1200 km. This snapshot in time will almost certainly look different by the time of publication, but illustrates the scale and dynamism of this segment of the industry.

There will be at least two major impacts to the space industry from these LEO mega-constellations, assuming they can surmount some significant technical and regulatory

hurdles. First, manufacturing satellites on this scale will require new automated assembly-line methods not yet tried by the space development industry. OneWeb intends to replace one-third of their fleet every year, so sustainment alone requires one new satellite every workday. New manufacturing methods and economies of scale will bring down the cost of satellite manufacturing, and those skills will eventually transfer to the rest of the industry.

The second major impact is to the Geosynchronous Earth Orbit (GEO) Comsat industry. The cost for bandwidth has been dropping for some time because of increasing capacity at GEO. Should the LEO constellations succeed, there will likely be increased price pressure. If broadband communication moves to the Voice-Over-Internet-Protocol enabled by the LEO and MEO constellations, it is unclear how well the large GEO Comsats will be able to compete. This could mean that satellite research dollars will move away from GEO satellites in favor of LEO. More fundamentally, success with the LEO constellations would erode the main advantages GEO holds over LEO; advantages of persistence and wide area coverage. The orbital regime chosen for space missions would then come down to cost and resilience.

NewSpace continues to leverage the technology developments coming from the universities, labs, and UARCS. New technologies are on display every year at the Utah State Small sat Conference, co-chaired by the Utah State Space Dynamics Lab and Johns Hopkins University Applied Physics Lab. Some of the new capabilities on display have included several methods of propulsion suitable for CubeSat and Small sats, many new uses for additive manufacturing, and greatly improved wideband communications. Electromagnetic tethers may be able to either generate power or use excess power to maneuver the satellite through the earth's magnetic field lines. Mission proposals have included constantly maneuvering satellites to confuse targeting by adversaries, and using constant propulsion to fly an imaging satellite beneath the F2 layer of the ionosphere, allowing even optics built into 6U CubeSat to image with better than 1 m resolution. It is difficult to predict which technology advancement will be the one to enable a new market, but it's a safe bet that the flow of technologies, coupled with business-savvy innovators and willing investors will continue to grow this disruptive industry.

Launch

The first part of the NewSpace ecosystem to gain traction was launch, and launch continues to be a key component. New launchers in development include suborbital systems for space tourism, some 20 new launch vehicles to serve the commercial small satellite market; DARPA and industry cofunded projects to kick-start rapid, reusable launch systems; and the SpaceX Falcon Heavy. A common feature of all these efforts is the dream of less expensive, more routine access to space to expand access to space.

The CubeSat community today relies on two sources for launch: rideshares and the International Space Station (ISS). NASA offers rides on commercial crew and resupply missions to the ISS, and a commercial firm, Nanoracks, operates what is effectively a CubeSat dispenser from the station. The advantage is economic launch, which would often constitute 80% of a mission's cost utilizing traditional launchers. The disadvantage is the very limited range of attainable orbits. The second source of launch, sharing the ride with other users, has become the mainstay of the industry. Several rideshare "bundlers" provide listings of costs and schedules. The downside of ridesharing is, of course, being at the mercy of the primary customer's schedule and orbit. One NewSpace company calculated that to achieve the equivalent of a Walker constellation, by launching on every available rideshare in every nearby orbit, it would take 30% more satellites than if the secondary controlled the launch. The new launch vehicle manufacturers hope to solve the restrictions of both the ISS and rideshares by offering individual launches. Selling points include the ability to put a

small sat in the desired orbit and within the desired schedule. Should this prove less expensive than today's two options, that would be an added benefit.

The NewSpace launchers have not yet come into the market reliably or with a launch cadence of mature launch companies but are expected to do so between 2018 and 2020, with the most capable of launchers able to insert up to 400 kg in LEO. If successful, these new launch companies will provide the small sat PM with significant new options and perhaps enable new markets. For the military, new launch companies may enable rapid replenishment in a contested space environment.

Satellite Servicing

The third potential game changer for traditional space is the promise of robotic satellite servicing. Five extraordinary manned Hubble servicing missions caught the world's attention from 1993 to 2009, but they were expensive, risky for the astronauts involved, and relied on a Space Shuttle that no longer flies. In 2010, McDonald, Dettwiler and Associates (MDA) of Canada proposed a commercial robotic satellite servicer, based in part on their extensive experience building and operating robotic arms for Space Shuttle and the ISS. The MDA Space Infrastructure Servicing (SIS) satellite would refuel existing commercial GEO satellites not designed for refueling. In the end, MDA could not close on the business case and did not build the system, but did seem to kick-start the interest of other organizations, both government and commercial. NASA demonstrated robotic refueling on the ISS in 2011. In 2012 DARPA announced Project Phoenix to visit derelict satellites and either bring them back to life or repurpose hardware. Phoenix has since died and been reborn as Robotic Servicing of Geosynchronous Satellites (RSGS), to fly a GEO robotic servicing demonstration mission in 2020. Several commercial companies and foreign governments continue to investigate and invest in satellite servicing concepts, although sometimes for different reasons. It seems only a matter of time.

Space servicing changes the calculus for satellite builders. In the short term, servicing can extend the life of existing satellites through added power and propulsion. In the mid-term, new satellites can be built with servicing in mind and upgrade components as needed. This becomes the equivalent of a submarine returning to port for refitting, allowing aging satellites to have modern capabilities. Servicers could also be used in debris mitigation, removing the largest derelict space objects before a potential collision or breakup event. And, because the greatest risk to a satellite continues to be launch failure, it may prove economical to manage this risk by launching with a small fuel load and refueling the satellite once it achieves orbit, allowing the use of a smaller and cheaper booster. In the long term, it may even be possible to refuel spacecraft with rocket fuel manufactured from the water found in asteroids or on the moon.

Regulatory Challenges

One of the challenges for PMs working in NewSpace is licensing. The United States has a decentralized system for licensing satellite operators, designed for traditional space but proving to be cumbersome for NewSpace.

The Department of Commerce, through the National Oceanic and Atmospheric (NOAA) Commercial Remote Sensing Regulatory Affairs Office has authority to license commercial

remote sensing satellites in the United States. NOAA defines remote sensing as the ability to actively or passively sense the earth's surface, which encompasses all bands of imagery, active radar, and passive RF sensing. NOAA has 120 days to review a license request through an interagency process that ensures the proposed satellite system is compliant with federal laws and regulations.

The licensing requirement was created to help the U.S. high-resolution commercial imaging industry operate without harm to national security. Regulations, however, are written broadly and require NOAA licensing of even the less capable and more numerous CubeSats. This has put a great deal of pressure on a small office not resourced for the flood of license applications [9].

Unfortunately, licensing is not a one-stop shop. A launch license must be obtained from the Federal Aviation Administration for a satellite launched from a U.S. territory. For the use of radio frequency spectrum, the company needs a license from the Federal Communications Commission, which is proving to be a major speed bump for the industry. The export of certain technical design data, equipment, or technology can require export licensing from the Department of Commerce or the Department of State. None of the offices issuing licenses have analytic teams dedicated to commercial space as of this writing. Large satellite companies employ licensing specialists to negotiate the maze, but for small companies trying to move quickly to market, licensing can be a significant hurdle for the PM or PjM, and should be a part of their training.

There is another major regulatory change on the horizon. Space traffic management—keeping track of satellites and debris, predicting conjunctions and collisions, and alerting owners of maneuverable satellites when they should move—has long been a default role of the U.S. military, which operates the world's most capable network of ground- and space-based sensors for tracking space objects. In the last few years, the U.S. Strategic Command has asked Congress to give that responsibility to a civil agency and let the military concentrate on national security space operations and defense [10]. The idea of a civilian space traffic manager has gained considerable traction, and in April 2016 legislation was introduced into the House to give that responsibility to the Federal Aviation Administration [11]. A civilian space traffic management agency looks to be on the horizon, and would mark a major change in the way satellite owners and operators interact with government regulatory agencies, and give PM's a new bureaucracy to master.

Space is becoming an international level playing field as other nations such as the UAE, Turkey, Iran, South Africa, Brazil, and South Korea make large investments in satellites and ground stations. The U.S. influence in the regulatory environment may be degraded over time in favor of international policy authorities such as the U.N. Commission on Peaceful Uses of Outer Space. It would be wise for the PM to maintain an international perspective when it comes to evolving space policies.

There is no better time in history to be a space professional, and in particular to work as a program or project manager. The upside is that the work can be extremely dynamic, and where many of yesterday's PM's were lucky to see one of their missions fly, tomorrow's PM are likely to work on many, very diverse missions. The down-side is that the Professional Body of Knowledge (PBOK) for program management is no longer sufficient to succeed in this increasing complex new world. It is a time for initiative, professional connectivity, and constant learning. The PM and PjM needs to embrace cognitive diversity in staffing and teaming, and focus not on the satellite but the value of the platform being built. The PM of tomorrow will need to have an excellent working knowledge of cyber threats and cyber security, to understand both traditional acquisitions and scrum development, and to stay current with a regulatory and technical environment that is changing faster than textbooks can be written.

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Tailoring Agile Techniques for Aerospace Project Management

Philip Huang

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SKUNK WORKS NEED TO GET UPDATED.

Tailoring Agile Techniques in Aerospace Project Management

Agile Program and project management is studied for the application of managing agile software projects. Agile management is described as "…an iterative, incremental method of managing the design and build activities of engineering, information technology and other business areas that aim to provide new product or service development in a highly flexible and interactive manner; an example is its application in Scrum, an original form of agile software development" [1]. Aerospace program management has become a disciplined field over the years with increasing levels of controls (and bureaucracy). This is not always appropriate for the manager who is looking for new approaches or is involved in higher risk activities such as managing research and development. Even in established and mature aerospace organizations there is a recognition that "…the present budget and competitive landscape require that we dispassionately assess our capabilities and approaches to ensure that we can be as successful in the future as we have been in the past." Further "… the organization must drive costs down and drive delivery times down while still keeping focused on the mission and doing the right thing for the sponsor (customer)…." (Dr. Michael Ryschkewitsch, JHUAPL, Laurel, MD, June 2015, unpublished discussions.) When doing things the "way they have always have done it," for protecting the organization's reputation, or keeping the existing organizational structure become the driving factor(s) behind making decisions on making updates or changing approaches, companies end up stuck, locked in, and lose competitiveness. The organization must not give in to a fear of making mistakes and, in doing so, lose opportunities to innovate, learn, and develop new unique abilities.

This chapter examines the emerging field of agile program management as it applies to Aerospace programs. Incorporating techniques that are derived from the Agile Manifesto and its movement and application to earlier work in alternate management techniques such as Skunk Works,* this chapter creates up-to-date applications of agile techniques to the management of aerospace programs. It is important to understand where agile project management may be applied and the potential challenges. Just as the agile movement started with the software engineering world, other newer movements from the current digital/information revolutions are also incorporated [2].

When to Use Agile Project Management

Agile program management is appropriate for programs and projects where the level of uncertainty is high which is often seen in high technology projects that are based primarily on new, not entirely existent, technologies. Some of these technologies are emerging; others are even unknown at the time of the project's initiation. The execution period of the project

* The marks SKUNK WORKS® and the Skunk Logo are registered in the United States Patent and Trademark Office, and in many other countries, in connection with a wide variety of goods and services. Now owned by Lockheed Martin Corporation, the marks were first used during World War II and are still used today. These marks represent the goodwill associated with the birthplace of many famous aircraft, as well as the research and development capability and cultural mindset that even today make the impossible happen.

is, therefore, devoted in part to identifying and developing new technologies, testing, and selecting among alternatives. This type of development project obviously entails high levels of uncertainty and risk due to the development of new and nonproven concepts, or a completely new family of systems.

These projects typically require extensive development and nonrecurring engineering costs (NRE). Their development frequently requires building an intermediate, small-scale prototype, on which new technologies are tested and approved before they are installed on the larger-scale prototype, or engineering model. System requirements are hard to finalize at the start of the project; they undergo multiple changes and involve extensive interaction with the customer. The system functions are of similar nature—dynamic, complex, and often ambiguous during development. A high tech system, on the "bleeding edge," is never completed before at least two, but very often even four, design cycles are performed, and the final system design freeze is never made before the second or even the third quarter of the project. The management style of these projects needs to be highly flexible to accommodate the long periods of uncertainty and frequent changes. Managers must live with continuous change for a long time; they must extensively increase interaction with all members of the project, be concerned with many risk mitigation activities, and adapt a "look for trouble" approach. One key element to success is to embrace innovation of high technology projects where many components and subsystem may have yet to be designed. Rapidly assessing every approach and performing quick trades is a key enabler for success. Often agile teams have members that hold multidisciplinary skills in order to keep the cost, schedule, and size of the team constrained.

History of Agile Techniques

In 1911, Frederick Taylor, in his study of the steel industry's management techniques, *The Principles of Scientific Management* [3], converged on four duties of management that are the core of his management system. First, scientific study should be used to determine the optimal method to perform a task, not the rule of thumb. Second, management should train workers in standardized processes, not rely on workers passing knowledge among themselves. Third, management should supervise workers to follow the developed methods. Fourth, management should free workers from the burden of planning. These principles created an environment where management planned and defined the work with little or no feedback from the workers, encouraging a top-down management approach and linear progress in assembly line phases. The clearly defined initial, one-time plan and execute methodology assumes the project is predictable, and is well understood at the start for clearly defined tasks and phases. Plan-driven development methods were practically the only management technique for organizations until the 1990s.

In the 1970s, Royce introduced an alternate development model that has commonly been misunderstood. Rather than prescribing the flawed Waterfall Method, which has been mistakenly attributed to Royce, he was recommending an iterative approach to improve the Waterfall Method. Royce even states, "I believe in this concept [Waterfall], but the

implementation described is risky and invites failure" [4]. Royce identified five things that must be addressed to reduce the risk of the Waterfall Method:

1. *Program Design Comes First*—Stay focused to solve the customer's real problem.
2. *Document the Design*—For saving and sharing information and what was learned.
3. *Do It Twice*—What was done must be fed back for verification and improvement (iterate).
4. *Plan, Control, and Monitor*—Keep a tight feedback loop to reduce cost of changes (incremental development).
5. *Involve the Customer*—It is essential to have the customer involved as much as possible.

The five items from Royce can be found in the foundation of agile methods.

Emergence of Agile Methods

For the past few decades, the software industry has made efforts to find alternatives to the top down, linear development management techniques, which originated in manufacturing. Testing after the development phase does not make sense in the software industry, since problems or flaws found would require changes to the design and possibly even the requirements. In the linear development process, a return to the design phase or farther back to the requirements phase would have major cost and schedule consequences. Software development needs to be able to respond quickly to changes and allow new ideas from the designer to be implemented. In 2001, a group of software developers drafted the Manifesto for Agile Software Development [5]. The manifesto called for the use of iterative methods for product development and emphasized the following four principles: individuals and interactions over process and tools, working software over comprehensive documentation, customer collaboration over contract negotiation, and responding quickly to change over following a plan. At first glance these four principles may appear to advocate unstructured projects with no methodology, but the implementation of agile techniques requires both consensus among the team and a high level of discipline to follow and execute the agreed-upon rules and methods.

Working software is the priority rather than detailed documentation. Expanding the concept to hardware and systems, this means that the working product takes precedence. Agile techniques can be tailored or modified differently for each project; there is no set method to fit every program. The main focus of every project, big budget or low cost, should always be based on the four main concepts from the Agile Manifesto.

Agile Techniques and Skunk Works

The Skunk Works rules of operation got their start on the Lockheed XP-80 project in 1943 when engineer, Clarence "Kelly" Johnson got the approval to create an experimental engineering department to begin work on the (then) secret Shooting Star jet

fighter [6]. Johnson was allowed to operate his engineering team effectively and efficiently using an unconventional organizational approach that broke the existing paradigms, and challenged an existing management system that stifled innovation and hindered rapid progress.

Kelly Johnson had three simple rules supporting his single fundamental belief "don't build something you don't believe in." His three basic principles are as follows:

1. It is more important to listen than to talk.
2. Even a timely wrong decision is better than no decision.
3. Do not halfheartedly wound problems—kill them dead.

Are Johnson's basic principles similar to the principles of the Agile Manifesto? Remember that the Agile Manifesto calls for the use of iterative methods for product development and emphasized the following principles: individuals and interactions over process and tools, working software over comprehensive documentation, customer collaboration over contract negotiation, and responding quickly to change over following a plan. Listening over talking is key in collaboration with the customer and interaction with the individuals of the development team. Even a wrong decision would allow a quick change as opposed to waiting to follow a plan. Elimination of a problem would be the first step to a working product. Johnson's principles are analogous to the principles of the Agile Manifesto. Enabling and maintaining these principles are crucial for the success of any project, but especially on innovative developments where funding is limited, schedule is tight, and the level of uncertainty is high. Johnson's 3 principles evolved into the 14 rules for Skunk Works.

Even if 7 of the 14 rules for Skunk Works seem to be focused on Lockheed processes or on military and government contracting, further analysis of all 14 rules reveal a correlation to the 4 basic principles of the Agile Manifesto. Table 24.1's left column lists the Skunk Works rules. The right column lists the principle of the Agile Manifesto related to the Skunk Works rule [7].

Beyond a Modernized Skunk Works

Just as the Skunk Works concepts have been updated and brought into the managing of agile teams, one can borrow concepts from the Zen of Python and apply to hardware, software, and the team (Table 24.2) [8].

Lessons Learned from an Agile Test Spacecraft Build

These lessons were drawn from a project that was characterized as a high tech project, that is, new, nonproven concepts requiring extensive development of technologies and system components [9]. The management style of high tech projects can be described as highly flexible to accommodate the long periods of uncertainty and frequent changes.

TABLE 24.1

Principles of Agile Elements in the Rules of Skunk Works®

1. The Skunk Works® manager must be delegated practically complete control of his program in all aspects. He should report to a division president or higher.	An empowered manager will have the ability to modify processes to the project's needs and the ability to select the best individual for the project. *P1: individuals and interactions over process and tools*
2. Strong but small project offices must be provided (both by the military and industry).	Empowered team members will have responsibility to quickly make the changes necessary for the project. A direct link between the development team and the sponsor will keep information flowing. *P1: individuals and interactions over process and tools* *P3: customer collaboration over contract negotiation*
3. The number of people having any connection with the project must be restricted in an almost vicious manner. Use a small number of good people (10%–25% compared to the so-called normal systems).	Similar to previous, team members that can contribute and have a stake in the project should be working the issues. *P1: individuals and interactions over process and tools* *P2: working software over comprehensive documentation*
4. A very simple drawing and drawing release system with great flexibility for making changes must be provided.	Keep the documentation system simple. Allow the changes to the documentation to be easily done. *P1: individuals and interactions over process and tools* *P2: working software over comprehensive documentation* *P4: responding quickly to change over following a plan*
5. There must be a minimum number of reports required, but important work must be recorded thoroughly.	Minimize the paperwork but important work must be configuration managed. *P1: individuals and interactions over process and tools* *P3: working software over comprehensive documentation*
6. There must be a monthly cost review covering not only what has been spent and committed but also projected costs to the conclusion of the program.	Taking this one step further: reviews of cost, schedule, and accomplishments need to be done on a regular interval. Depending on the project, this could be daily, weekly, or monthly. The team needs to determine the interval. *P1: individuals and interactions over process and tools* *P3: customer collaboration over contract negotiation*
7. The contractor must be delegated and must assume more than normal responsibility to get good vendor bids for subcontract on the project. Commercial bid procedures are very often better than military ones.	Get a good, solid bid/proposal that fits the needs of the project. *P1: individuals and interactions over process and tools* *P2: working software over comprehensive documentation* *P3: customer collaboration over contract negotiation*
8. The inspection system as currently used by the Skunk Works®, which has been approved by both the Air Force and Navy, meets the intent of existing military requirements and should be used on new projects. Push more basic inspection responsibility back to subcontractors and vendors. Don't duplicate so much inspection.	Tailor process for the project. *P1: individuals and interactions over process and tools* *P2: working software over comprehensive documentation*
9. The contractor must be delegated the authority to test his final product in flight. He can and must test it in the initial stages. If he doesn't, he rapidly loses his competency to design other vehicles.	Test as early and as much as possible. Final test in the appropriate environment is critical for project success. *P1: individuals and interactions over process and tools* *P2: working software over comprehensive documentation* *P4: responding quickly to change over following a plan*

(*Continued*)

TABLE 24.1 (*Continued*)

Principles of Agile Elements in the Rules of Skunk Works®

10. The specifications applying to the hardware must be agreed to well in advance of contracting. The Skunk Works® practice of having a specification section stating clearly which important military specification items will not knowingly be complied with and reasons therefore is highly recommended.	Bare minimum requirements need to be agreed upon as the start. Test results will identify solutions and issues that need to be reported to the sponsor as quickly as they are found. *P3: customer collaboration over contract negotiation* *P4: responding quickly to change over following a plan*
11. Funding a program must be timely so that the contractor doesn't have to keep running to the bank to support government projects.	With the stress of tight schedule and technology innovation, a shortage of funding would stop project momentum. *P3: customer collaboration over contract negotiation*
12. There must be mutual trust between the military project organization and the contractor, the very close cooperation and liaison on a day-to-day basis. This cuts down misunderstanding and correspondence to an absolute minimum.	A direct link from the team to the sponsor will allow for transparency and a continuous flow of information (both directions) *P3: customer collaboration over contract negotiation*
13. Access by outsiders to the project and its personnel must be strictly controlled by appropriate security measures.	For classified programs this is obvious. But in general distractions to the development team should be kept to a minimum. *P1: individuals and interactions over process and tools*
14. Because only a few people will be used in engineering and most other areas, ways must be provided to reward good performance by pay not based on the number of personnel supervised.	The development team should be recognized for working outside of the existing corporate process and procedures. *P1: individuals and interactions over process and tools*

TABLE 24.2

Concepts from the Zen of Python Applied to Agile Project Management

Adapted from the Zen of Python	Agile Management of the Hardware and Software
Beautiful is better than ugly.	Clean (clarity) is better that dirty (clutter).
Explicit is better than implicit.	Explicit is mandatory. Readability counts.
Simple is better than complex.	Simple elements rarely fail; complex elements fail in complex ways.
Complex is better than complicated.	Complicated inserts additional failure points.
Flat is better than nested. Sparse is better than dense.	Modify and upgrade to an element without impacting the total system
Special cases aren't special enough to break the rules.	For Agile to succeed, discipline rules.
Although practicality beats purity.	Only gold plate if actually requiring gold plating.
Errors should never pass silently. Unless explicitly silenced.	Addressing errors should stay as a top priority.
In the face of ambiguity, refuse the temptation to guess.	Test to remove uncertainty.
There should be one—and preferably only one—obvious way to do it.	Again test to find that preferred option.
Now is better than never. Although never is often better than *right* now.	Now is good if well thought through.
If the implementation is hard to explain, it's a bad idea.	Again, clarity eliminates the chance of failure points to creep into the system.
If the implementation is easy to explain, it may be a good idea.	

Managers must live with continuous change for a long time; they must extensively increase interaction, be concerned with many risk mitigation activities, and adapt a "look for trouble" mentality. The key to the project's success was the following elements.

Individuals and Interactions

For the project, a small, cohesive team was created, which consisted of experienced staff of appropriate seniority, who were not just technically experienced but also had worked in high-pressure situations. Key team members, the subsystem leads, were allowed to make decisions quickly and were given direct access to the sponsor. The project organization was flattened. People and interactions are emphasized. The key team members were allowed to call in "subject matter experts" (e.g., mechanical manufacturing, magnetic scientists, Electromagnetic Interference (EMI)/Electromagnetic Compatibility (EMC) engineers, antenna designers, assemblers,) but these "experts" were used on a part time, as needed, basis and were not a continuous expense to the project.

The program manager, leader of the team, reported directly to the head of the development organization and had the authority to implement whatever changes were needed for the success of the project. The program manager had to institute changes from the existing process and structure, pull in experts as needed, and push out personnel who were not needed. Most importantly, this high-ranking official provided instant authenticity and legitimacy to the project and staff. With the ability to implement the ideas and decisions specific to develop the project, the staff was empowered to meet the expectations of the sponsor while maintaining cost and schedule.

To promote and insure easy and accessible communication among subsystems, the key team members were collocated. Being able to nearly instantaneously locate the appropriate people for any type of discussion enabled the team to quickly execute design trades and decisions and to gage the implications of each as they arose.

Emphasis on Approaches Toward a Working System

Typical space missions follow a well-defined process flow to design, develop, and deliver high-quality ultra-reliable satellite for NASA sponsors. But in order to meet the cost and schedule while dealing with uncertainty, the project used a nonlinear process development flow to address issues needing attention as soon as possible. Using a nonlinear flow, processes were modified from the nominal development of space missions to emphasize the requirements and completion of the project. Hardware testing was deferred to the flight system level, forcing integration and test to be involved early, while the automation, coordination, and training of mission operations was moved later in the system development (nonlinear time line). Engineers tested as these boards and subsystems were built. Issues and problems were fixed as they were being found. This followed the fundamental premise of "build a little, test a little, and learn a lot."

In the 1970s, Rear Admiral Meyer's philosophy of "build a little, test a little, learn a lot" drove the testing and milestones of the Aegis system. The "build a little, test a little and learn a lot" is used extensively in agile hardware developments. Testing is done in small incremental steps. This effective approach drives short tests or proto-test. With agile software development, there is a correlation in exploratory testing, which is an approach to software testing that is concisely described as simultaneous learning, test

design and test execution. Cem Kaner, who coined the term in 1983 [10], now defines exploratory testing as "a style of software testing that emphasizes the personal freedom and responsibility of the individual tester to continually optimize the quality of his/her work by treating test-related learning, test design, test execution, and test result interpretation as mutually supportive activities that run in parallel throughout the project." Key elements of proto-tests include that an actionable element must be available at the end of the test. A proto-test is used throughout the engineering design phase and into the development phase.

Test-driven development and agile hardware development testing allows the team to tackle smaller problems first and then evolve the system as the requirements become more clear later in the project cycle. The advantages of this test-driven or proto-test environment include the following:

- Robust elements evolved in small steps.
- The test suite acts as documentation for the functional specification of the final system.
- The system uses automated tests, which significantly reduce the time taken to retest the existing functionality for each new build of the system.
- A test failure provides a clear idea of the tasks that must be performed to resolve the problem. This also provides a clear measure of success when the test no longer fails. This increases confidence that the system actually meets the customer requirements.

However, engineering teams still need to consider traditional testing techniques, such as functional testing, user acceptance testing, and system integration testing.

The engineering team focused on tailoring development to the needs of the sponsor and the sponsor's risk acceptance. To maximize the utility of design reviews and reviewers, the project used one review, the aptly-named Only Design Review (ODR). The requirements were discussed verbally and the Computer Aided Design (CAD) model, or simulation analysis, was projected and manipulated in real-time to discuss the design concept and features. These ad-hoc discussions gave presenters the ability to effectively answer questions in detail, allowing the review team access to the smallest details of the design. Reviewers were intentionally selected such that they would add value. Many informal and unscheduled peer reviews were held throughout the duration of the program.

Documentation was minimized but all component drawings were captured and remain in storage under configuration management. Since the amount of staff-hours and schedule expended to simply support a typical space program signature cycle simply cannot be justified on a cost-conscious program, the signature list for most drawings consisted of just the originator and the lead engineer. Drawings and documents that affect other subsystems were approved by all the affected parties.

Flexibility was used when choosing manufacturing sources and methods. Ordinary non-critical parts were procured based on turn-around time and lowest cost. Parts requiring high precision and tolerance were made using in-house NASA-certified manufacturing facilities, which have the capability to produce extremely tight tolerance parts and allow the engineering staff to conveniently monitor and direct the fabrication process. Mechanical structures were manufactured using files created directly from the design models, allowing machinists to program the machine quickly and still maintain quality. The team used technology to help reduce cycle time and cost.

Collaborative Interface with Sponsor

Having direct access to the key project staff, the sponsor was an active collaborator in the development of the space system. The sponsor participated in all major reviews, enthusiastically providing feedback and inputs on tasks and issues with emphasis on the agreement of requirements and assuring that the test criteria will adequately fit the end users' needs. The sponsor engaged in frequent face-to-face meetings and was able to regularly participate in the status meetings. Questions were immediately clarified avoiding the cost of idle time. Rapid tailoring of the requirements allowed for a cost-efficient and effective approach. Being aware of the issues, willing to stay flexible, and making adjustments as the project moved forward, the sponsor was an agile sponsor.

Responding to Dynamic Scheduling and Tasking Approaches

For the project, a colocated interdisciplinary team was established with a vested interest in the schedule, cost, and adjustments to the scope of the project. Daily team reviews were held using a variation of the scrum board. A scrum board (commonly used in software agile practices) was used to track all tasks and issues allowing adjustments to the highest priority. The scrum board not only identified which team member was responsible and when the task would be completed, but also allowed issues to be carried forward and final decisions to be made later. Tasks that were dependent on the completion of another task were easily seen, and bottleneck issues were given the highest priority. Responding to change is emphasized, rather than extensive planning. The scrum board also allowed part-time team members access to the status of the tasks and who to engage if more information was needed. The scrum board visual demonstrates the speed that each program element was progressing through the project and eliminated overly formal action item tracking and meeting summarization.

TABLE 24.3

Recommendations to Promote Agility in New Project Development

1. Utilize a small, empowered team with a direct link to the sponsor or customer. The customer will be engaged and well informed—embedding seamlessly into the team.
2. Empower the team members, by making each lead not only have the authority and responsibility for their subsystem but also for the interfaces and interactions with all subsystems.
3. Require the project manager report to a figure of authority in the company, reporting to the highest possible level (above the matrix organization).
4. Leverage outside help, or experts on a part time, as needed basis.
5. Co-locate the technical leads, systems engineer, quality/mission assurance manager, and program manager for at least some portion of the day, every day to review all tasks and issues, including cost and schedule.
6. Provide interactive design reviews to help the program staff uncover issues with their concepts or designs. Select reviewers that can contribute and provide input, ideas, and insight.
7. Analyze and test as early as possible to mitigate issues, but specifications and requirements will be continually updated throughout the development.
8. Tailor processes to the requirements of the project; the use of the existing system/processes may be too much or too little.
9. Minimize the number of recorded documentation, but important work must be configuration managed.
10. Find a solution to an issue/problem; implement and make sure the issue/problem is closed to the satisfaction of every key member of the project team. Do not let a problem with a solution linger.

If the four sections sound like "Agile," they are! The Manifesto for Agile Software Development values is: "Individuals and interactions over processes and tools, working software over comprehensive documentation, customer collaboration over contract negotiation and responding to change over following a plan." The recommendations in Table 24.3, derived from this sample project, should be used to promote agility to sustain new project development.

Conclusion

While the aerospace sector works on the strategy elements to create innovation while continuing to leverage existing methodologies, the sector should consider agile, dedicated teams designed to rapidly pivot in response to the needs of the customer. As the sector continues to develop cutting edge technology for the traditional, complex missions, agile teams, in contrast, will focus on driving development of technology and processes for the customer and will leverage rapid iteration for innovation, where every step informs the next advancement toward a final solution—learning by doing.

By allowing agile teams to effectively customize processes that do not bring substantial value to the customer, that can slow down the development process, and that can grow costs, the sector could be more effective in support of smaller-scale constrained work with an acceptance of these changes.

Consideration of agile management is not a call to abandon or eliminate existing aerospace sector processes, but compromises must be made to leverage past lessons learned on the large scale, complex missions with a willingness to try new approaches. Tailoring existing, proven processes for the customer will, above everything, do what makes sense for the customer, insuring the work supports the customer and delivers a project meeting the customer needs.

Projects have schedule risk due to uncertainty in the outcomes of future design and risk management actions. Similar to other complex systems it is not possible to predict long-term schedule details with high confidence. If long-term schedules are prepared in detail, then these details become inaccurate and require rescheduling after a few months of work. In the short term, knowledge of resource availability, delivery schedule, and funding level are better understood. The detail schedule should be developed using rolling wave planning to minimize having to rework the detailed planning whenever an unexpected event changes the work and requires modifying the plan for future work in order to meet the intended milestones. Rolling wave planning is a method of managing in the presence of future uncertainty due to risk by using short work periods and progressively adding more details in the next work period. More details to design requirements, funding availability, and schedule can be added as the information becomes available. Rolling wave planning of tasking and funding can continue to use Work Breakdown Structures (WBS) and scheduling using Microsoft Project™. The schedule should be updated regularly to maintain 2–4 months of future-detailed schedule [11]. Agile scrum teams use "sprints" as a set period of time during which the team completes specific work with a review at the end of "sprint." During the review, the team evaluates the tasks from this period of work and plans the tasking for the next work period (sprint) considering upcoming milestones, funding, and resource availability.

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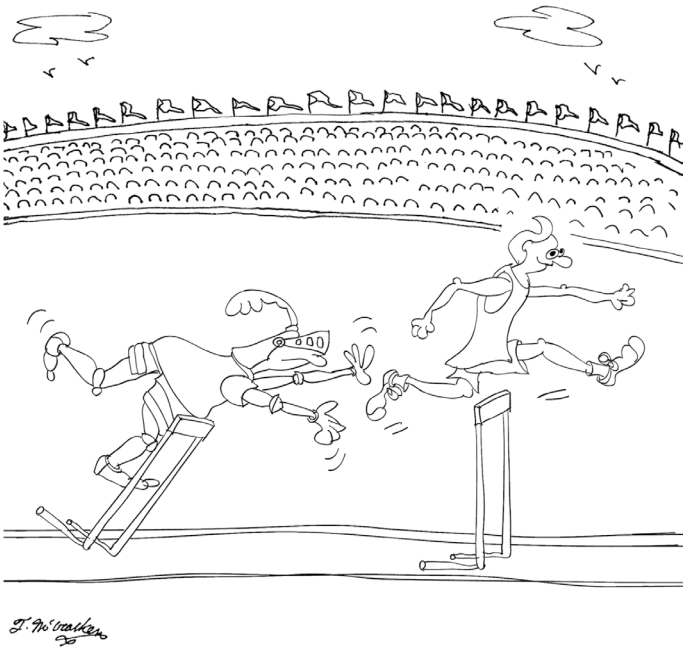
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Model-Based Systems Engineering

Annette Mirantes

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AT TODAY'S PACE WE NEED AGILITY

Introduction

Model-Based Systems Engineering (MBSE) is defined by the International Council on Systems Engineering (INCOSE) as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." So, what does that mean for the typical space systems engineer and what benefit does that provide to the project? This chapter on the emerging area of MBSE for space systems will give project managers an overview of it, describe how it can be useful for the project team, and describe some of the methodologies and tools that might be a good fit for a project.

Overview of MBSE

The use of models is not new in spacecraft development. Thermal models, guidance and control models, and structural models are just some of the subsystems that use models to capture and store subsystem information as well as define and visualize the relationships among the information. The model is used to produce subsystem outputs and products as the design is realized. With MBSE the system engineer performs the same tasks in the system lifecycle and still produces the same products (see Table 25.1), but the information is stored in a centralized repository (model) and it is the creation of that model that is the primary focus of the lifecycle (Figure 25.1). The system model encompasses both the system design and the system specification (Table 25.1).

How does MBSE change traditional systems engineering? Space systems engineers still perform their role from a very document-centric perspective. Typically the system engineer would get a document from a previous program and then manually update that document. Each document in the lifecycle is produced, reviewed, and placed in some type of document repository. Requirements specifications, concept of operations (ConOps) document, architectural description documents, system design specifications, and test case specifications are examples of some of the documents produced by the space systems engineer. A significant amount of time is spent throughout the project lifecycle developing, reviewing, and maintaining these documents. If the time is not spent to maintain these documents, they quickly become outdated, obsolete, or inconsistent. And more importantly, the document-centric approach provides no connection between the information in these documents. It is up to the systems engineer to recognize and make sure that a change in one document is reflected accurately, and if that change impacts anything in the system that is captured in another document. If so, that document needs to be updated as well. Requirement changes in one document can have the biggest impact to operations, architecture, design, and test. Any change has to be manually assessed and the change has to be applied to any other documents if needed.

In MBSE a system model is built that stores not only the system information but the underlying relationships. This allows the team to capture system requirements and behaviors in a model that the team can access and view at any time. With a model a change can be introduced and quickly assessed for its impact to the system. With MBSE the space "system" can be modeled as we have traditionally modeled subsystems and components.

TABLE 25.1

NASA Project Life-Cycle Phases

	Phase	Purpose	Typical Output
Formulation	Pre-Phase A concept studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, and identify potential technology needs.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mockups
	Phase A concept and technology development	To determine the feasibility and desirability of a suggested new major system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, and needed system structure technology developments.	System concept definition in the form of simulations, analysis, engineering models, and mockups and trade study definition
	Phase B preliminary design and technology completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mockups, trade study results, specification and interface documents, and prototypes
Implementation	Phase C final design and fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D system assembly, integration and test, launch	To assemble and integrate the products to create the system, meanwhile developing confidence that it will be able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products
	Phase E operations and sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
	Phase F closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

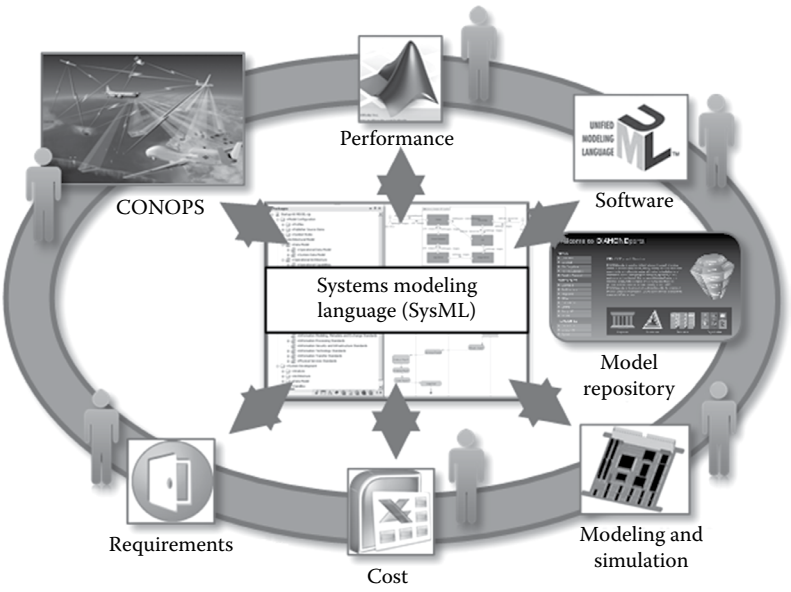


FIGURE 25.1
System model.

Benefits of MBSE

MBSE moves the system engineering task from document centric to model centric. The model will centralize the system information and can automatically propagate a change made in one area of the system to the areas impacted by that change, and the model allows you to immediately visualize the impact of that change. This provides benefits in the following areas.

Costs

MBSE can be a cost saver in the amount of time needed to develop, review, and maintain required documents. When using a system model, the maintenance of documentation is streamlined to maintenance of the model. Documents are created from the model.

Consistency

A change introduced to the system (requirement, behavior) can be immediately propagated in the model to areas impacted by the change. This reduces risk as well since making a change to the system no longer requires someone to manually review and update all potentially affected documents.

Communication

A model facilitates communication among the team and can be used to communicate the system to external stakeholders and reviewers as well. System information is available to the team at all times, and using a consistent representation of the data allows the team to "speak the same language."

Impact of Change

A system model can be of great help in analyzing the impact of a change to the system. Trade studies and impact assessments can benefit from the ability to make a change to the system model and see immediately how that change affects the system.

Getting Started

So how might a program get started with MBSE? Above all other decisions associated with converting to MBSE, the program must assert its dedication to use it. Without buy-in from the team (at least a majority) and program management, using a different approach on a program would likely fail. Once there is a solid commitment to using MBSE, there are three decisions that need to be made as early as possible—process, tools, and language.

Processes

The first step to using MBSE on a space program is to decide how MBSE will be used to provide the most value to the program. Like any tool it should be used to make the team's job easier, but that also involves some preparation by the team. The system engineering lead should document how the tool will be used by the team. Here are some questions to consider:

- What is to be accomplished by using a tool? Review current process and determine where a tool can help. Is the tool to manage requirements traceability? Will the tool be used to perform impact assessments, design alternatives, and/or trade studies? What documents will the model generate?
  - Example [1]: The NASA Asteroid Redirect Robotic Mission (ARRM) developed a minimum set of MBSE capabilities to mature a Phase A concept. MBSE was used to generate four key SE deliverables: Requirements, Operations Concepts, Product Breakdown Structure, and System Block Diagrams. The system engineering lead developed the process:
    - Identify top-level requirement
    - Create operations concept of a mission to satisfy these requirements
    - From the operations concept identify functions (activities) that must be implemented
    - Allocate these functions to elements
    - Write requirements for these functions
    - Identify interfaces between elements
    - Write interface requirements
    - Link requirements
    - Iterate
- Will the system model be used as input to work later in the design and development for software, hardware, reliability, performance, etc.? Will the model continue test cases used to verify the system?

By asking these questions, the scope and usage of the system model is defined so that the team knows when the model is complete.

Once the MBSE process is defined for the program, the team can decide on the best methodology.

Methodologies

An MBSE methodology is a combination of the process defined earlier and the methods and tools used to execute that process. Some well-known modeling methodologies and tools are listed here, with links to additional information:

- IBM Rational Rhapsody Designer for Systems Engineers (http://www-03.ibm.com/software/products/en/ratirhapdesiforsystengi). (Accessed January 10, 2017)—An integrated tool environment (that uses the industry standard languages Systems Modeling Language (SysML) and Unified Modeling Language (UML). It contains features specifically for
  - Architecture, design, and special
  - Requirements analysis and elaboration
  - Trade study analysis
  - Prototype and simulation
  - Testing and validation (with add-on)
  - Design documentation generation
  - Allows collaboration with other modeling tools
  - Includes DoDAF, MoDAF, and other DoD frameworks
- Vitech GENESYS (http://www.vitechcorp.com/products/genesys.shtml). (Accessed January 10, 2017)—An enterprise-ready tool that uses SysML to provide
  - Integrated requirements management
  - Behavior models
  - Architecture development
  - Validation and Verification
  - Impact assessment of configuration changes
  - DoDAF framework
- JPL Europa System Model Framework (Figure 25.2) [2]—An internally developed methodology for the NASA Europa mission that, according to recent published literature, has the potential to be used across NASA centers for the following:
  - Managing multiple architectural alternatives
  - System design
  - Requirements management
  - Documentation
  - V&V

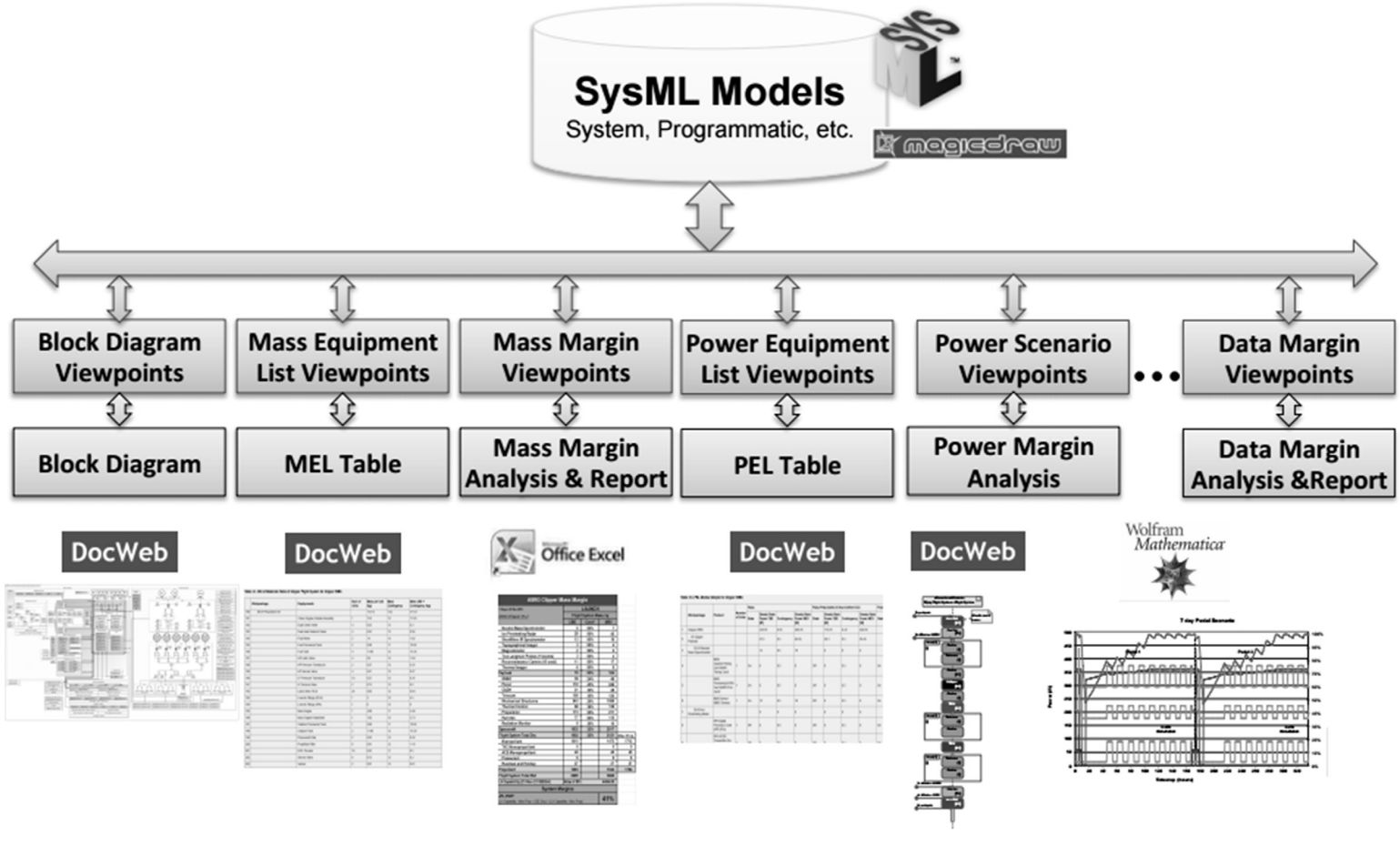


FIGURE 25.2
Europa system model framework.

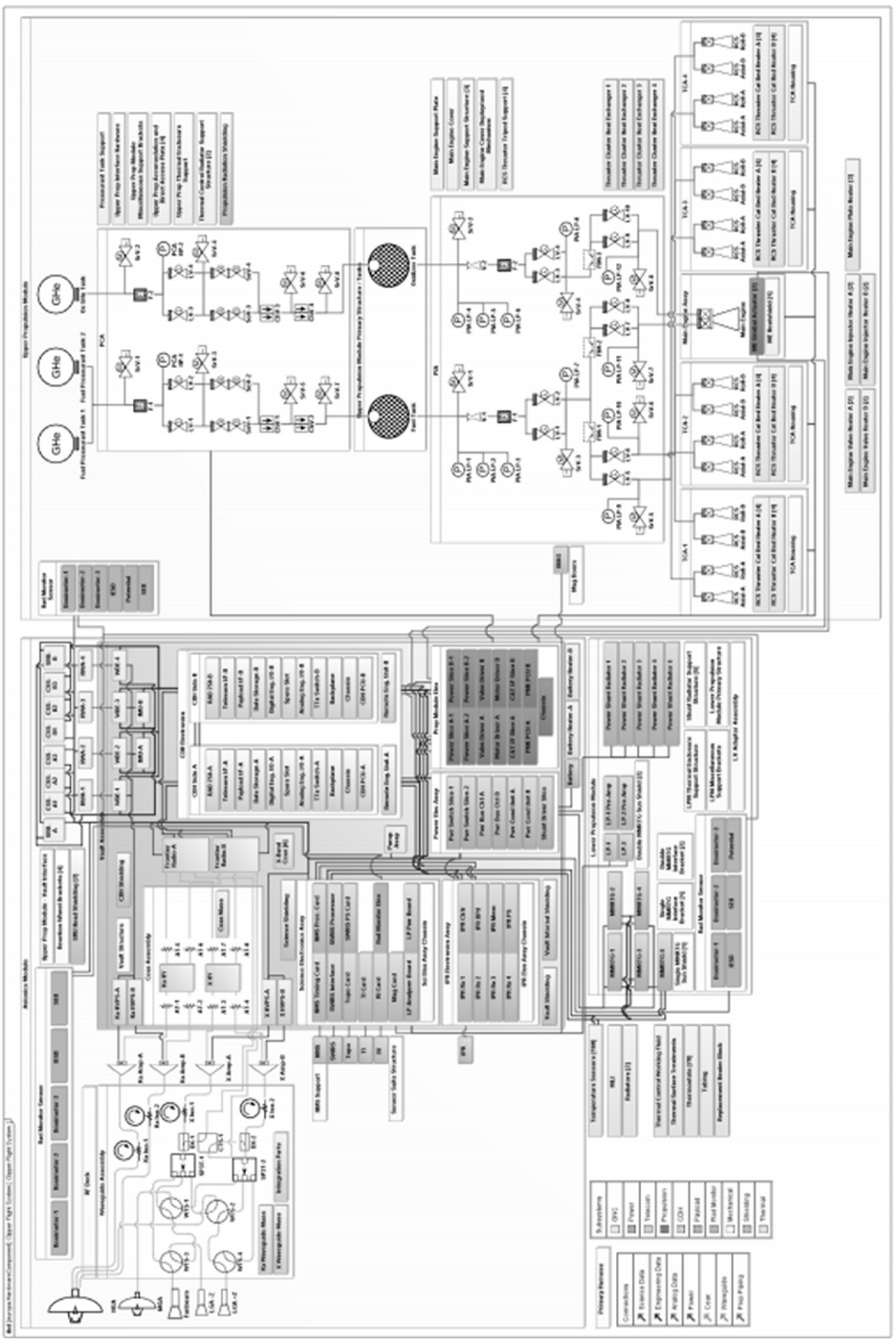


FIGURE 25.3
Spacecraft block diagram.

The JPL methodology is "space-centric," with the potential to produce most of the work products required on a NASA mission, such as a spacecraft block diagram shown in Figure 25.3 [2].

Potential Pitfalls

The use of MBSE for space systems development has encountered the same types of challenges that any new tool, process, or approach would. Here are numerous issues that can come up when switching from a previous approach to systems engineering to a model-based one, but they are all usually based on the question: Why change from something that's working?

Space systems engineering relies heavily on "lessons learned" and is usually slower to embrace new paradigms than engineers who work on terrestrial-based systems. Space missions, especially deep space missions, are not as risk tolerant. Knowing the answer to the "Why change?" question is key. Here are some ways to address this issue:

- Remember that above all, the program must be dedicated to using MBSE. There will probably be a few members of the team who are not on-board with the change, but the lower that number, the better chance for success.
- The tool allows them to spend more time on systems engineering tasks and less on document management.
- There must be a process in place that shows how the tool will be used and how it will add value to the systems engineering process. Having a clear and communicated process in place at the beginning of the program is key.

Conclusion

MBSE can be an enabling technology for systems engineers on a program that seeks to transition from a document-based process to a model-based process that centralizes the data for the system lifecycle. If there is buy-in from the team and management, using MBSE where it addresses the program challenges versus a one-size-fits-all mentality can allow a program to reap the benefits of lower cost and lower risk.

References

1. Cichy, B. *MBSE on ARRM Presentation*. Goddard Space Flight Center NASA/GSFC Greenbelt, MD, March 2016.
2. Nichols, D. and Lin, C. *Integrated Model-Centric Engineering: The Application of MBSE at JPL through the Life Cycle*. INCOSE MBSE Workshop Jet Propulsion Laboratory, Pasadena, CA, January 2014.


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Appendix A: Commonly Used Acronyms in Aerospace Program/Project Management

ACS	Attitude Control System
ACWP	Actual Cost for Work Performed
AO	Announcement of Opportunity
AoA	Analysis of Alternatives
AR	Anomaly Reporting
ATP	Authority to Proceed
BAA	Broad Agency Announcement
BAC	Budget at Completion
BCR	Baseline Change Request
BCWP	Budgeted Cost for Work Performed
BCWS	Budgeted Cost for Work Scheduled
BOE	Basis of Estimate
BUE	Bottom-Up Estimate
C&DH	Command and Data Handling
CA	Control Account
CADRe	Cost Analysis Data Repository
CAM	Control Account Manager
CCB	Change Control Board
CDR	Critical Design Review
CDRL	Contract Data Requirements List
CER(s)	Cost Estimating Relationship(s)
CFE	Contractor Funded Equipment
CI	Configured Item
CJCSI	Chairman of the Joint Chiefs of Staff Instruction
CLIN	Contract Line Item Number
CM	Configuration Management
CMMI	Capability Maturity Model Integration
CMMI®-DEV	Capability Maturity Model® Integration for Development
CMP	Configuration Management Plan
CNF	Cost-No-Fee
CO	Contacting Officer
COR	Contracting Officer Representative
COTS	Commercial-Off-The-Shelf
CP	Cost Plus
CPFF	Cost-Plus-Fixed-Fee
CPI	Cost Performance Index
CRM	Continuous Risk Management
CSO	Chief Safety Officer
CV	Cost Variance
DAG	Defense Acquisition Guidebook
DARPA	Defense Advanced Research Projects Agency
DAS	Defense Acquisition System

DCMA	Defense Contract Management Administration
DL	Direct Labor
DoD	Department of Defense
DSC	Defensive Space Control
EAC	Estimate at Completion
EAR	Export Administration Regulations
ECP	Engineering Change Proposal
EGSE	Electrical Ground Support Equipment
EM	Engineering Model
EMC	Electromagnetic Compatibility
EME	Electromagnetic Emission
EMI	Electromagnetic Interference
EMS	Electromagnetic Susceptibility
EPO	Education and Public Outreach
ETC	Estimate to Complete
EVM	Earned Value Management
FAR	Federal Acquisition Regulation
FB	Fringe Benefit
FCA	Functional Configuration Audit
FF	Finish-to-Finish
FFP	Firm Fixed Price
FM	Financial Manager
FMEA	Failure Mode Effect Analysis
FNET	Finish No Earlier Than
FNLT	Finish No Later Than
FPR	Forward Pricing Rate
FS	Finish-to-Start
FTE	Full Time Equivalent
G FLOPS	Giga (billion) Floating Point Operations Per Second
G&A	General and Administrative
GDS	Ground Data System
GEO	Geosynchronous Orbits
GFE	Government Funded Equipment
GFP	Government Funded Property
GNC	Guided Navigation and Control
GPMC	Governing Program Management Council
GSA	Government Services Administration
GSE	Ground Support Equipment
IC	Intelligence Community
IGY	International Geophysical Year
IMS	Integrated Master Schedule
IMU	Inertial Measurement Unit
IPAO	Independent Program Assessment Office
IRAD	Internal Research and Development
IRU	Inertial Reference Unit
ISR	Intelligence, Surveillance, and Reconnaissance
ITAR	International Traffic and Arms Regulations
JCIDS	Joint Capabilities Integration and Development System
JCL	Joint Cost and Schedule Confidence Level

JHU/APL	Johns Hopkins University Applied Physics Laboratory
JROC	Joint Requirements Oversight Council
KDP	Key Decision Point
LEO	Low Earth Orbit
LOE	Level of Effort
MAM	Mission Assurance Manager
MDAP	Major Defense Acquisition Program
MDC	Miscellaneous Direct Costs
MEL	Master Equipment List
MEO	Medium-Earth Orbits
MFO	Must Finish On
MGSE	Mechanical Ground Support Equipment
MOPs	Mission Operations
MR	Management Reserves
MSO	Must Start On
NAS	National Academy of Science
NASA	National Aeronautics and Space Administration
NICM	NASA Instrument Cost Model
NOAA	National Oceanic and Atmospheric Administration
NRE	Nonrecurring Engineering
OBS	Organizational Breakdown Structure
ODC	Other Direct Cost
OH	Overhead
ONCE	One NASA Instrument Cost Model
OSC	Offensive Space Control
PBS	Product Breakdown Structure
PCA	Physical Configuration Audit
PDM	Project Development Manager
PDR	Preliminary Design Review
PDS	Planetary Data System
PDU	Power Distribution Unit
PER	Pre-Environmental Review
PERT	Program Evaluation and Review Technique
PI	Principal Investigator
PjM	Project Manager
PMB	Performance Measurement Baseline
PMBOK	A Guide to Project Management Body Of Knowledge
PMI	Project Management Institute
PNT	Position, Navigation, and Timing
PO	Purchase Order
PoP	Period of Performance
PP&C	Project Planning and Control
PPBES	Planning, Programming, Budgeting, and Execution System
PRA	Probabilistic Risk Assessment
PSR	Pre-Ship Review
PWS	Performance Work Statement
RACI	Responsible, Accountable, Consult, Inform
RAM	Responsibility Assignment Matrix
RFI	Request for Information

RFP	Request for Proposal
RFQ	Request for Quote
RIDM	Risk-Informed Decision Making
RM	Resource Manager
RM	Risk Management
ROM	Rough Order of Magnitude
SAM	Systems Assurance Manager
SAT	Simplified Acquisition Threshold
SATCOM	Satellite Communications
SEI	Software Engineering Institute
SF	Start-to-Finish
SIR	Systems Integration Review
SME	Subject Matter Expert
SMEX	Small Explorers
SNET	Start No Earlier Than
SNLT	Start No Later Than
SOO	Statement of Objectives
SOW	Statement of Work
SPI	Scheduled Performance Index
SRA	Scheduled Risk Assessment
SRB	Standing Review Board
SS	Start-to-Start
SSA	Space Situational Awareness
SSP	Source Selection Plan
SV	Scheduled Variance
T&M	Time and Materials
TAA	Technical Assistance Agreement
TCPI	To Complete Performance Index
TINA	Truth in Negotiations Act
TR	Technical Representative
TRL	Technology Readiness Level
TRR	Test Readiness Review
USGS	United States Geological Survey
VAC	Variance at Completion
VAP	Van Allen Probes
WBS	Work Breakdown Structure

Appendix B: Useful Project Manager, System Engineer, and Lead Engineer Checklists

Major Formal System Reviews

- System Requirements Review (SRR)
- Conceptual Design Review (CoDR)
- Preliminary Design Review (PDR)
- Critical Design Review (CDR)
- Mission Operations Review (MOR)
- Pre-Environmental Review (PER)
- Pre-Ship Review (PSR)
- Flight Operations Review (FOR)

Checklist of Major Required Program/Project Manager Duties

- Manage Deviation Requests
- Program or Project Manager for all programs/projects
- Develop a SOW
- Develop a WBS
- Develop a schedule
- Estimate the cost and labor
- Develop a Program or Project Plan
- Develop Configuration Management Requirements
- Develop and Control Required Document List
- Monitor Schedule via Software Tool
- Implement Risk Management Assessment
- Ensure a System Assurance Manager Is Assigned to the Project
- Define Signature Authority
- Prepare a System Safety Program Plan
- Contact HES if There Are Issues or Spaceflight Program
- Develop Organizational Chart
- Lead Project Team
- Conduct Program Status Reviews
- Conduct Technical Reviews
- Follow Testing Requirements
- Conduct Formal Change Control
- Support Contract Closure

Checklist of Major System Engineering Documents

- ☐ Systems Engineering Management Plan
- ☐ Software Development Plan
- ☐ Configuration Management Plan
- ☐ Environmental Design and Test Requirements Document
- ☐ EMC/EMI Control Plan
- ☐ Mission Requirements Document
- ☐ Performance Assurance Implementation Plan
- ☐ Systems Requirements Documents, including
  - Payload Requirements
  - Ground System Requirements
  - Spacecraft Requirements
- ☐ System Interface Control Documents, including
  - Payload to Spacecraft ICD
  - Spacecraft to Launch Vehicle ICD
  - Spacecraft to Ground ICD
- ☐ Contamination Control Plan
- ☐ Spacecraft Disposal Plan
- ☐ System Verification Plans
- ☐ Verification Matrix
- ☐ System Test Procedures
- ☐ Orbital Debris Assessment
- ☐ Launch Site Support Plan

Suggested Subsystem Technical Reviews

- ☐ Alignments Peer Review
- ☐ Autonomy Preliminary Design Review/Critical Design Review
- ☐ Avionics Preliminary Design Review/Critical Design Review
- ☐ Electronic Board/Box Engineering Design Review
- ☐ FPGA Engineering Design Review
- ☐ Guidance and Control Peer Reviews (Pre-Preliminary Design Review and Precritical Design Review)
- ☐ Ground System Engineering Design Review
- ☐ Instrument Preliminary Design Review/Critical Design Review
- ☐ Mechanical Subsystem Peer Review
- ☐ Mechanisms Peer Review
- ☐ Mission Design Reviews
- ☐ Power Preliminary Design Review/Critical Design Review
- ☐ Propulsion Preliminary Design Review/Critical Design Review

- RF Engineering Design Review
- Software Design Review
- Thermal Peer Reviews (Pre-Preliminary Design Review and Precritical Design Review)
- Coordinate Transformation/Reference Frame Peer Review

Suggested Electrical and Mechanical Design Checklist

- Design Requirements
- Statutory Requirements
- Regulatory Requirements
- CAD (Computer-Aided Design) Program
- Drawing Numbers
- Documentation Level
- Signature Authority
- Data Sharing
- Estimates
- Schedule
- Reviews
- Checking
- Record Keeping
- Deliverables
- Verification


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Appendix C: Suggested Processes, Specifications, and Other Documentation

1. **Spacecraft Autonomy Development Process**

   Processes and Specifications

   Autonomy Requirements Specification

   - Autonomy Test Plan
   - Autonomy Lessons Learned Document

   Documents and Forms

   - Autonomy Requirements Inputs
   - Autonomy Requirements Review Report
   - Autonomy Requirements Traceability Matrix
   - Autonomy Release
   - Autonomy Test Report (may include various test procedure reports)
   - Lessons Learned

2. **Command and Data Handling, Power Distribution Unit, and Power Subsystems Development Process**

   Processes and Specifications

   - Subsystem/Component Development Plan
   - Avionics/Power Hardware Specifications (may be a collection of discrete component level documents)
   - Subsystem/Component Verification Plan
   - Subsystem-Level Test Plan (may be a collection of discrete box-level documents)
   - Subsystem/Component/Acceptance Test Procedures
   - Subcontracted component specifications

   Documents and Forms

   - Subsystem/Component Acceptance Test Reports (may be a collection of discrete box-level documents), including
     - Thermal Tests Reports
     - Mechanical Tests Reports
     - EMI/EMC Test Report
     - Magnetics
   - Subsystem End-Item Data Package (may be a collection of discrete box-level documents)
   - Subsystem Integration Readiness Review Report (may be a collection of discrete box-level documents)
   - Subsystem Integration Readiness Review Action Items and Responses

- Subcontracted component End-Item Data Package
- Lessons Learned

3. **Contamination Control Development Process**

   Process and Specifications
   - Contamination Control Plan
   - Launch Site Contamination Control Plan
   - Controlled Facility Certification Report(s)
   - Cleanroom Training Media

   Documents and Forms
   - Contamination Control Report
   - Contamination Analysis and Modeling Statement of Work(s)
   - Contamination Analysis and Modeling Reports
   - Precision Cleaning and/or Contamination Analysis Test Results (Hardware Verification Matrix)
   - Lessons Learned

4. **Electrical Ground Support Equipment Development Standards (EGSE) Requirements Specification**

   Processes and Specifications
   - EGSE Hardware/Software Interface Control Documents

   Documents and Forms
   - Lessons Learned

5. **Electrical/Electronics Board and Box Development Process**

   Processes and Specifications
   - Box Requirements Specification
   - Board Requirements Specification(s)
   - Flight Model Board Acceptance Test Procedure
   - Box Acceptance Test Procedure
   - Box Ground Support Equipment Safe-to-Mate Procedure
   - Box Test Plan
   - Box Assembly and Integration Procedure
   - Box Ground Support Equipment User's Manual
   - Vibration Test Procedure
   - Thermal Vacuum Test Procedure

   Documents and Forms
   - End Item Data Package
   - Integration Liens
   - Flight Box Test Data and Report
   - Lessons Learned

6. **Electromagnetic Compatibility Control (EMC) Process**
   Processes and Specifications
   - EMC Control Plan
   - EMC Test Plans and Procedures (Component/Subsystem)
   - EMC Test Plans and Procedures (Instrument)
   - EMC Test Plans and Procedures (System)

   Documents and Forms
   - EMC/EMI Test Reports
   - Lessons Learned

7. **Fault Management Engineering Process**
   Processes and Specifications
   - Fault Management Architecture Document
   - Fault Management Requirements
   - Fault Management Design Specification Document
   - Fault Management Verification and Test Plan
   - Fault Management Test Procedures

   Documents and Forms
   - Fault Analysis Documentation
   - Completed Verification Matrix
   - As-run Fault Management Test Procedures
   - Fault Management Test Reports
   - Lessons Learned

8. **Spacecraft Field Programmable Gate Array (FPGA) Design and Development Process**
   Processes and Specifications
   - FPGA Requirements Specification

   Documents and Forms
   - Source Code
   - Fuse Files
   - Lessons Learned

9. **Guidance and Control (G&C) Development Process**
   Processes and Specifications
   - G&C Requirements Document
   - G&C System Verification Matrix
   - G&C System Test Plan
   - G&C System Test Procedures
   - G&C Post-Launch Checkout Procedures

- G&C On-Orbit Alignment and Calibration Plan/Procedures (Procedures may consist of scripts generated and maintained by Mission Operations with G&C inputs and monitoring.)
- G&C Sensor and Actuator Electrical/Mechanical Interface Document
- Flight Software Interface Control Document (for data transfer, parameters, protocols, and timing requirements for G&C algorithms embedded in the flight software)
- G&C Algorithm to Testbed Interface Control Document
- G&C/Mission Design Interface Control Document
- G&C/Mission Operations Parameter Upload Interface Control Document
- G&C-Navigation Interface Control Document.

Documents and Forms

- G&C Sensors and Actuators End Item Data Packages
- G&C Bench Test Reports
- G&C Polarity Test Reports
- G&C Performance Test Report
- G&C Pre-Launch Parameter Review Report
- G&C Lessons Learned
- G&C System Error Budget or Error Tree

10. Ground System Development Process

Processes and Specifications

- Ground System Development Plan
- Ground System Specification
- MOC to Ground Support Equipment Interface Control Document (ICD)
- I&T Ground System Set-Up and Checkout Test Procedure
- Testbed/Hardware-in-the-Loop (HIL) Spacecraft Simulator Requirements and Design Document
- Umbilical Ground Support Equipment Requirements and Design Document
- Ground System Trade Studies Finding
- Ground System Contingency and Disaster Recovery Plan
- Ground System Test Plan/Procedure
- Ground System Longevity Plan
- Miscellaneous I&T Ground Support Equipment Requirements and Design Document

Documents and Forms

- Ground System Setup and Checkout Test Results

11. Harness Development Process

Processes and Specifications

- Harness Requirements Document
- Harness Design Specification

- Reference Designation List
- Test Plan
- Detailed Design
- Harness Fabrication Specification

Documents and Forms

- As-Built Configuration
- Verification and Test Results
- Work Order Travelers/Work Execution Documents
- Test Procedures
- Lessons Learned

12. Instrument Development Process

Processes and Specifications

- Instrument Requirements (part of the System Engineering requirements database)
- Instrument Specifications
- Instrument Test Plan
- Instrument Comprehensive Test Procedure
- Instrument Operations Manual
- Instrument Software Specifications

Documents and Forms

- Planning Meeting Notes
- Instrument EMC Test As-run Procedures and Summary Report
- Instrument Software Test Report
- As-run Calibration Procedures
- Calibration Test Results
- Instrument Functional Test Report
- Instrument Acceptance Test Report
- Assembly Notes
- Instrument End-Item Data Package
- Instrument Readiness Review Report (minutes and action items)
- Lessons Learned

13. Spacecraft Integration and Test Process

Processes and Specifications

- I&T System Test Plan
- Environmental Test Plan (may be part of I&T System Test Plan)
- Transportation Plan
- TIRDOC (or equivalent)
- Test Procedures
- Test Scripts

- I&T Test Configurations
- Test Cable Specifications

Documents and Forms

- Harness Installation and Test Records
- Component Integration Test Records
- Instrument Integration Test Records
- Phasing Test Records
- RF Compatibility Test Records
- Deployment Test Records
- Performance Test Records
- Environmental Test Records
- Test Script Log Files
- Launch Site Test Records
- Launch Pad Test Records
- Limited Life Items Status History
- Red Tag/Green Tag Items Status
- Lessons Learned

14. Mechanical/Structure Development Process

Processes and Specifications

- Mechanical System Development Plan
- Mechanical System Specifications
- Alignment Test Plan
- Mechanical Handling Plans
- Assembly Plans
- Mechanical Test Procedures
- Field Planning Documents
- Flight Predicted Loads

Documents and Forms

- Fabrication Readiness Review Reports
- Environmental Test Reports
- Structure Test Reports
- Pre-Environmental Alignment Procedure Report
- Post-Environmental Alignment Procedure Report
- Final Analysis Report
- Mechanical / Structural Qualification Report
- As-Built Drawing Package
- Lessons Learned
- Alignment budget

- Structural Models and Analysis
- Correlated Structural Models with Flight Predictions

15. Mission Design Process

Processes and Specifications

- Mission Design Requirements Document
- Orbital Debris Assessment
- Launch Target Specification
- Mission Design Flight Operations Readiness Test Plan
- Mission Design Launch Readiness Test Plan
- Mission Design—Navigation Interface Control Document
- Mission Design—Guidance and Control Interface Control Document
- Mission Design—Mission Operations Center Interface Control Document—Mission

Documents and Forms

- Design Requirements Verification Matrix
- Mission Design Flight Operations Readiness Test Reports
- Mission Design Launch Readiness Test Reports
- Mission Design Data Products
- Nominal Spacecraft Trajectory Files and Mission Profiles
- Lessons Learned
- Delta-V Budget

16. Mission Operations Development Process

Processes and Specifications

- Mission Concept of Operations
- Mission Operations Development Plan
- Mission Operations Plan
- Launch and Early Operations Plan
- Mission Operations System Test Verification Matrix, if required
- Contingency Handbook
- Standard Operating Procedures
- Contingency Operating Procedures
- Flight Constraints Document
- MOPS Configuration Management Plan
- Mission Operations Launch Preparation Schedule
- Mission Operations Test Plan

Documents and Forms

- Mission Operations Test Reports
- Lessons Learned

17. **Parts, Materials, Planning, and Testing Process**

    Processes and Specifications

    - Parts Control Plan
    - M&P Control Plan

    Documents and Forms

    - Preliminary, As-Designed and As-Built Parts and Materials List
    - Problem Parts and Materials Lists
    - Parts, Materials, and Processes Control Board Meeting Minutes
    - EEE Parts Derating Analyses Forms
    - GIDEP Alerts and Advisory Disposition Records (Maintained in GIDEP Database)
    - Lessons Learned
    - EEE Parts Derating Analyses

18. **Propulsion System Development Process**

    Processes and Specifications

    - Propulsion System Specification
    - Propulsion System Statement of Work
    - Propulsion System Performance Analysis
    - Propulsion System Test Plan
    - Propulsion System Integration Procedure
    - Command and Telemetry Requirements
    - Concept of Operation Requirements

    Documents and Forms

    - Subsystem Level Integration and Test Reports
    - Propulsion System Vendor Manufacturing Readiness Review Report
    - Propulsion System Integration and Functional Test Report
    - Propulsion System Pre-Acceptance Test Review Report
    - Propulsion System Receiving Inspection Test Report
    - Propulsion System Consent-to-Ship Review Report
    - Propulsion System End-Item Data Package
    - Lessons Learned
    - Propellant Budget

19. **Reliability Engineering Process**

    Processes and Specifications

    - Reliability Analyses Review packages
    - Reliability Analyses Reports (includes methodology, assumptions, and results)
    - Specifications and Statements of Work for subcontracted reliability analyses and reports

Documents and Forms

- Mission/System Critical Items List (CIL)
- Lessons Learned
- Models and Analyses:
  - PRA-Probability Risk assessment
  - FTA-Fault Tree Analysis
  - FMEA-Failure Modes Effects Analysis
  - WCA-Worse Case Analysis

20. Requirements Engineering

Processes and Specifications

- Requirements Database, with
  - Mission Requirements
  - Segment Requirements (if noted in the System Engineering Management Plan)
  - Element Requirements (e.g., Spacecraft, Ground System, Operations Center, Instruments)
  - Subsystem Requirements
- Environmental Requirements, which may include
  - Component and System Environmental Requirements
  - Electromagnetic Control Requirements
  - Contamination Control Requirements
  - Safety and Mission Assurance Requirements, which may include
    - Product Assurance Requirements
    - Safety Requirements

Documents and Forms

- Verification Planning Matrix
- Verification Plan
- Requirements Closure Documentation
- Lessons Learned

21. Mission Science Process

Processes and Specifications

- Mission Science Requirements
- Science Operations Plan
- Data Management Plan
- Calibration Plan for each science instrument

Documents and Forms

- Lessons Learned document
- Archived science data products
- Published scientific results
- Deliverable reports required by sponsor

22. **Software Development Process**

    Processes and Specifications
    - Software Development Plan
    - Software Requirements Document
    - Software Architecture Document
    - Software Design Document
    - Software Acceptance Test Plan

    Documents and Forms
    - Software Acceptance Test Report
    - Software Defect Reports
    - Lessons Learned

23. **Instrument Flight Software Development Process**

    Processes and Specifications
    - Instrument Flight Software Development Plan
    - Instrument Flight Software Requirements Document
    - Task Communication Graph
    - Configured Software
    - Instrument Software Specification

    Documents and Forms
    - Instrument Flight Software Requirements Peer Review Report
    - Lessons Learned

24. **Systems Engineering Process**

    Processes and Specifications
    - Systems Engineering Management Plan
    - Software Development Plan
    - Configuration Management Plan
    - Component/System Environmental Specification
    - EMC/EMI Control Plan
    - Mission Requirements Document
    - Performance Assurance Implementation Plan
    - Systems Requirements Documents, including:
      - Payload Requirements
      - Ground System Requirements
      - Spacecraft Requirements
    - System Interface Control Documents (ICD), including
      - Payload to Spacecraft ICD
      - Spacecraft to Launch Vehicle ICD
      - Spacecraft to Ground ICD
    - Contamination Control Plan
    - Spacecraft Disposal Plan

- System Verification Plans
- Verification Matrix
- System Test Procedures
- Orbital Debris Assessment
- Launch Site Support Plan

Documents and Forms

- Completed Verification Matrix
- As-run System Test Procedures
- Lessons Learned
- Mass Budget
- Power Budget
- Data (Volume/Rate) Budget

25. Ground Facility Process

Processes and Specifications

- Ground Facility Service Level Agreement
- Ground Facility Network Operations Plan (NOP)
- Ground Facility Contingency Procedures
- Ground Facility Standard Operating Procedures (SOP)

Documents and Forms

- Maintenance and Repair Records
- Shift Reports
- Ground Facility Routine Inspection Checklists
- Lessons Learned

26. Systems Engineering Standards

Processes and Specifications

- Specific requirements for specifications, tests, plans, and procedures defined in individual documents

Documents and Forms

- Lessons Learned

27. Space Flight System Test Requirements

Processes and Specifications

- Specific requirements for specifications, tests, test plans, and procedures

Documents and Forms

- Lessons Learned
- Specific requirements test reports

28. Thermal System Development Process

Processes and Specifications

- Thermal Systems Development Plan
- Thermal System Specifications

- Instrument Thermal Environmental Test Specification
- Instrument Final Flight Predicts
- Subsystem Thermal Environmental Test Plans
- Instrument Final Flight Predicts Report

Documents and Forms

- Spacecraft Thermal Environmental Test Plan
- Spacecraft Final Flight Predicts Report
- Multi Layer Insulation (MLI) layup drawing
- MLI Data Sheet
- MLI installation process
- Flight temperature sensor installation drawing
- Flight heater/thermostat installation drawing
- Instrument Thermal Test Report
- Subsystem Thermal Environmental Test Reports
- Spacecraft Thermal Vacuum (TV) Test Report
- Subcontracted Hardware End-Item Data Package
- Instrument End-Item Data Package (may include appropriate items mentioned here)
- Spacecraft End-Item Data Package (may include appropriate items mentioned here)
- Thermal Systems Performance Report
- Lessons Learned
- Analysis Documentation (without Correlated Model)
- Analysis Documentation (with Correlated Model)

29. Space Flight Mission Development Process

Processes and Specifications

- NONE

Documents and Forms

- Lessons Learned

30. Radio Frequency (RF) Subsystem Development Process

Processes and Specifications

- RF System Requirements (per System Engineering Management Plan)
- RF System Test Plan/Procedures
- RF System Integration Procedures
- RF System EMC Test Plan/Procedures
- RF System Software Specifications (when required by program)
- RF System Software Operations Manual (when required by program)

Documents and Forms

- RF System Pre-Environmental Test Results Report
- RF System EMC Test Results Report

- RF System Acceptance Test Report
- RF System End-Item Data Package for Integration and Test
- Lessons Learned
- RF Link Budget
- National Telecommunications and Information Administration (NTIA) Frequency Approval


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