

The background of the cover is a deep blue space filled with a dense field of space debris. Various satellites with solar panels, cylindrical modules, and smaller fragments are scattered across the frame, creating a sense of a crowded and potentially dangerous orbital environment.

Linda Dawson

WAR IN SPACE

The Science and Technology
Behind Our Next Theater of Conflict

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Our Next Theater of Conflict**



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*To my family—Mom and Dad, my sisters Judi and Patti,
and my husband Allan.*

Preface

My first book was *The Politics and Perils of Space Exploration*, published by Springer in 2017. This was a summary of primarily human space exploration and the way that politics shaped how NASA would proceed in the future, particularly after the Moon landing. The future of space exploration has become increasingly dependent on other countries and private enterprise. That first book provides a complete overview of the “new” US space program, which has changed considerably over the past 50 years.

War in Space summarizes the science and technology contributing to space defense and the weaponization of outer space. The primary emphasis is on the efforts of the United States, although the activities of other nations that have an adversarial relationship with the United States are discussed. The resulting defensive programs are summarized. A discussion of a possible war in space should contain a historical summary of how we got into the Space Race and define the status of spacecraft in Earth orbit. After researching all aspects of outer space as a theater of war, I remain hopeful that methods of deterrence for a war in space are successful.

I am a big fan of the way that science fiction depicts conflict in outer space, but as a scientist and engineer, I understand that the reality is much more serious and concerning to those of us on Earth than what is depicted in books and on the movie screen. I wanted to write this book to tell the story of how space exploration, presence in Earth orbit, and military efforts have been intertwined throughout the Space Race and will remain so moving forward.

My career in aerospace engineering includes working at NASA in Houston on the Space Shuttle program for years prior to the first launch and past the first couple of launches. I was hired to be an Aeronautical Flight Controller for Mission Control. This is the first vehicle that would operate as an airplane on re-entry, requiring the development of a series of operational tools. The Space Shuttle orbiter vehicle was already designed, developed, and being built in the mid- to late

1970s. When I was hired by NASA, the prototype Enterprise was about to be transported and drop-tested from a 747 airplane to test its glide capabilities. I became familiar with the Shuttle vehicle and NASA operations and learned to understand how stable the orbiter vehicle would behave during its re-entry maneuvers. After initiating a de-orbit burn, the orbiter would go through a series of S-turns designed to slow the spacecraft down prior to landing. No other combination airplane/spacecraft had flown at hypersonic speeds outside of the Earth's atmosphere. There were a lot of unknowns. My group investigated other hypersonic aircraft such as the SR-71, the X-15, and experimental lifting bodies to gain insight into the behavior of the orbiter as a glider. As it turned out, the orbiter vehicle was very stable and never became unstable in its descent.

One of my major tasks was to help develop the flight rules for the orbiter primarily for entry operations in addition to abort re-entry. The development of these rules required participation in extensive simulations for de-orbit and re-entry. I developed and conducted some of these studies using a re-entry simulator flown by Shuttle astronauts. Another component of my job was to estimate how much fuel was necessary to control the vehicle in case of stability problems. After the de-orbit burn, the only control for the orbiter vehicle comes from small reaction control jets, which are used for orbital maneuvering and control during entry or orbit maneuvers in the highest part of the atmosphere. If a control jet fails or another control problem requires a jet to stay on or off, vehicle control is maintained by the opposite reaction control jets staying on to compensate and maintain control. This type of failure uses extra fuel. To conserve fuel and save weight, only so many of these malfunctions can be accommodated. Therefore, the failures are prioritized as the most or least likely. After extensive simulations, the final entry fuel budget at the time reflected my simulation study for entry failures.

I am currently a retired professor from the University of Washington, an author, and a STEM promoter for women and girls. I hope that women are inspired by my my career and find their own path in the field of space science.

Finally, I hope this book provides a technical and historical background to understanding how orbiting spacecraft are a vital component to our daily life and how enemy threats could initiate a war in space and disrupt life as we know it today. Space science and the investigation of celestial bodies are essential for the future of mankind and the preservation and betterment of Earth. As on the surface of the Earth, diplomatic methods must prevail in order to keep the peace in outer space.

Acknowledgments

I would like to thank Maury Solomon of Springer Publishing for supporting me as the author to tell the story of space warfare as well as Hannah Kaufman for patiently guiding me to the completion of the manuscript. Also, my sister Judi Brodman for her edits and encouragement, and my husband Allan for his constant support.

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Life Without Satellites

*“Space is now a potential battle zone...the Air Force wants to ensure
“space superiority,” which he says means “freedom from attack
and freedom to maneuver.”*

—General John Hyten, head of the US Strategic Command¹

Introduction

Our daily lives are increasingly dependent on space technology currently orbiting the Earth. As the world becomes more tech savvy, it also becomes more closely tied to the communication and timing of satellite networks. The list of activities that rely wholly or in part on the proper operation of satellites includes television signals, emergency transmissions, business transactions, military surveillance data, and weather and climate predictions and evaluations.

There are many ways that satellite signals could be disrupted. Some are natural, such as a massive solar storm, while others may be the result of a cyber-attack, a laser weapon employed by an enemy nation, or destruction caused by artificial space debris. Evidence shows that the capability already exists to interrupt or destroy crucial satellite networks.

¹Ignatius, David. The Washington Post. 16 Mar 2017. War in space is becoming a real threat. [Internet] [cited 2018 Apr 20]; Available from: https://www.washingtonpost.com/opinions/war-in-space-is-becoming-a-real-threat/2017/03/16/af3c35ac-0a8f-11e7-a15f-a58d4a988474_story.html?noredirect=on&utm_term=.4f1aea9fd3fb

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The more dependent we are on satellite communication and performance, the more vulnerable we are to attacks, either natural or manmade. Governments around the world are beginning to address the resilience of their space infrastructures, beefing up cyber security and the way data are transmitted.

For a moment, let's reflect on what it would be like to live a day without satellites...

A Fictional Timeline of Satellite Disruption

Noon: Any Day in the Future

The day begins like any other. There are no explosions, no alarms, no panicked text messages about an impending attack or sudden disaster. The Sun comes up just as it always has, and people move along as they have always done, except for a handful of seemingly minor disruptions.

Cellphones bring most residents the latest emails or text messages. However, in the morning, most television signals are interrupted or gone completely. Most residents experience some inconvenience as they continue their activities of the day. Those driving in cars notice that the navigation system has gone offline. Customers cannot pay for their lunch with their bank card. Delivery package personnel are having difficulty locating destinations and scanning packages into the system. Those flying in airplanes watch movies, work, or play games offline, unaware that the crew is unable to communicate with air traffic control. Without satellite phones, those far out at sea or stationed in the desert are now isolated from the rest of the world. What seemed to many like a short-term glitch is becoming a longer-term reality. Rapid communications are grinding to a halt, and the world is no longer tied together in one neat bundle.

4:00 pm

It's becoming obvious that something is terribly wrong, but no one can identify a single incident that could cause such widespread disruption. No one had predicted a solar flare or any natural phenomenon that would cause such extensive consequences. No one reported any explosions or terrorist activity.

Concern turns into a crisis and the issuing of a security alert. Presidents and prime ministers begin to gather their emergency teams. Events continue to add to the threat of global stability, especially with the sudden loss of the Global Positioning System (GPS).

What does this all mean? How did it happen? Who and what are affected by the ensuing chaos?

GPS and Time Signals

GPS is a silent partner that helps us navigate from one place to another (see Fig. 1.1). GPS services are provided by the Navstar (short for Navigation System using Timing And Ranging) satellite network orbiting the Earth every 12 hours (see Chap. 2 for details). It has also become a valuable component for companies and services, making deliveries more efficient while providing specific directions for emergency services to reach individuals in need much quicker. On a more global level, GPS provides the necessary data for planes to land in isolated areas and for vehicles of all types to be tracked. Military operations await the transmitted information on enemy locations and troop movements. Anybody traveling in secluded and distant locations can be left stranded from such communications, including fishermen at sea and hikers in faraway lands.



Fig. 1.1. GPS-enabled smartphones have a location accuracy to within a 16-ft radius under open sky.² Image Credit: *US Air Force*

GPS satellites provide a vital link to time synchronization (see Fig. 1.2). Receivers on the ground, including auto systems, smartphones, or tablets, pick up time signals from orbiting satellites. A comparison of the time signals from outer space and the time stored in the receiver is used to calculate the distance to the satellite. Additionally, if three satellites are available, the latitude and longitude of the receiver can be determined.

² GPS.gov. [Internet]. c2017. GPS Accuracy. [cited 2018 Apr 20]; Available from: <https://www.gps.gov/systems/gps/performance/accuracy/>



Fig. 1.2. The Global Positioning System III Satellite Laser Ranging (GPS III SLR).
Image Credit: NASA

Without knowing it, the world has come to depend on these accurate time signals from space. Complex networks connect and communicate with each other, creating an infrastructure synced together by time. Internet protocols and methods depend on accurate time stamps as well as other complex business and financial transactions. Packets of data are transmitted between computers along with their individual time stamps. Time synchronization is a critical component for computer networks to function. Without the ability to accurately synchronize the time, the computers are at risk. This becomes an emergency situation. It is doubtful that the critical infrastructure controlling so many applications is prepared for a major GPS disruption.³

³Jackson, William. GCN Technology, Tools and Tactics for Public Sector IT. 12 Nov 2013. The serious side of GPS, where timing is everything. [Internet] [cited 2018 Apr 20]; Available from: <https://gcn.com/articles/2013/11/12/gps-timing-position.aspx?m=1>

8:00 pm

When the GPS signals stop transmitting, backup systems using accurate clocks on the Earth's surface kick in. However, the tiniest of inaccuracies begin to creep into the system within a few hours. A fraction of a second in one location compared to another causes the system to trip once again. The Internet slows and finally stops working altogether. Similar resources such as the Cloud also fail.

The systems that support the functioning of our major resource management services are in jeopardy. The power systems of the energy sector require precise GPS inputs to deliver an efficient and reliable power system as it synchronizes services in power networks. Now, such systems are not receiving data. At the same time, global financial services and computer systems are failing to communicate with each other and transmit data. The time-stamped ATM, credit card, and market transactions halt. People encounter difficulties paying for merchandise, conducting bank transactions, and receiving packages. Transportation systems, relying on GPS data for safe and efficient operations, face possible danger. Aircraft no longer have GPS aided navigation data to use inflight and assist with landings. Management systems for controlling commercial fleets and rail systems are no longer able to provide traffic data and collision avoidance input.⁴

The first power cuts are initiated as network grids struggle to meet demands. Numerous computerized systems switch to manual backup systems, causing delays and confusion. Some cities experience additional transportation issues when some traffic lights and railway signals default to red. Satellite phone services fail and mobile phones lose their GPS capability.

10:00 pm

By this time, aviation authorities must decide whether or not to ground commercial aircraft. A majority of flights have already been cancelled due to loss of satellite communications and GPS. The ability to predict and understand future weather patterns is a key contributor to aviation safety. Traditional meteorological methods using balloons and ground and ship observations are still important, but forecasting in the modern age has become increasingly dependent on satellite data. The aviation industry needs forecasts addressing turbulence, winds, and bad weather in order to make real-time safety decisions and alter affected flight paths. Although aircraft radar is capable of detecting bad weather or turbulence, crews rely on constant updates from the ground, and in some cases, other aircraft. These updates and alerts allow aircraft to keep track of weather patterns in their flight path and make appropriate changes. These data become more important in remote areas or over the oceans, where direct observations may not be available. Without weather

⁴Homeland Security. National Risk Estimate: Risks to U.S. critical infrastructure from Global Positioning System disruptions. 2011. <https://rntfnd.org/wp-content/uploads/DHS-National-Risk-Estimate-GPS-Disruptions.pdf>

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satellite data, an aircraft could fly into a serious thunderstorm, causing severe turbulence and leaving many passengers injured or distressed. As flights are cancelled, travelers are stranded in many locations far from home.⁵

Midnight

The first full “day without satellites”⁶ is ending. The impact is overwhelming. Daily activities are now all being affected, and a sense of panic is becoming the norm. Communications, transport, power, and computer systems have already been severely disrupted. Security alerts are posted at an all-time high. Emergency measures are being executed, including dispatching the National Guard to inner cities. Government officials warn that food supply chains will soon break down. Those without television or computer access listen to local radio news broadcasts speculating about the causes for the chaos.

Each day will bring new challenges and further disruption unless backup systems can take over at least the minimal load to provide basic resources. Satellite images are no longer available as a critical tool to help rescue workers respond to world disasters. Scientists are no longer able to keep track of the long-term effects of climate change. There will be no more data to show the diminishing Arctic ice cover, the health of crops, environmental atmospheric issues, or troop movements. Will cities become managed by the military to prevent looting and violence? Will hostile countries take advantage of the lack of intelligence data?

The irony here is that satellite technology, not originally designed for the average citizen, has now become an indispensable part of our lives. The infrastructure we all rely on has become increasingly dependent on space technology. We are all tied to satellites, and without them, the world would be a very different place.

Space Warfare: Timing Is Everything

In January 2016, when the US Air Force took one GPS satellite offline, an inaccurate time (only 13 millionths of a second) was accidentally uploaded to the clocks onboard 15 other satellites. This caused all of the satellites to lose their time synchronization, sparking a disruption for more than 12 hours in equipment around the world that depended on GPS timing. Emergency services in some parts of North America stopped functioning. Backup systems took over and prevented a major disaster, but global communications networks began to fail. Electrical

⁵Union of Concerned Scientists. What are satellites used for? <https://www.ucsusa.org/nuclear-weapons/space-weapons/what-are-satellites-used-for#bf-toc-3>

⁶The Arthur C. Clarke Foundation. A day without satellites. 22 Dec 2015. [Internet] [cited 2018 May 29]; Available from: <https://www.clarkefoundation.org/2015/12/a-day-without-satellites/>

power grids experienced irregularities. Even BBC digital radio was unable to transmit programming for 2 days in some areas.⁷

We envision the Global Positioning System as a network of satellites that provides us with maps and directions. This calculated and transmitted navigation data is made possible by a system closely linked by time. Each satellite in the GPS constellation (24 needed as a minimum) has multiple atomic clocks onboard. Atomic clocks are designed to measure the precise length of a second as the time it takes a caesium-133 atom to oscillate a precise number of times. The clocks are synchronized with each other to an accuracy of a nanosecond using the Coordinated Universal Time (UTC) (the time standard used across the world).⁸ The satellites continually broadcast their time and position information down to Earth, where GPS receivers in ground equipment from cellphones to airplanes acquire signals and use the minuscule differences in their arrival time to determine an exact position.

According to the Department of Homeland Security, 11 of the 16 critical industries identified by Presidential Policy Directive⁹ rely on precision timing. Defined as critical, these industries affect the civilian infrastructure: communications (including cell phones), finance, power distribution, and other linked networks. Military capabilities that depend on precision timing include secure communications, datalinks, sensor management, electronic warfare, network operations and management, and command and control.¹⁰

The US military requires reliable backup capabilities that allow it to be less dependent on satellite data. To do so, it must find new and comprehensive ways to identify threats to US timing systems. This means developing network operations that create, maintain, and improve timing sources and precision. There are many ways of measuring and distributing timing that do not rely on GPS or navigation systems. Examples include DARPA's Chip-Scale Atomic Clock and palm-sized Atomic Clock with Enhanced Stability (ACES).¹¹

Before GPS, Long Range Aids to Navigation (LORAN) was used to aid navigators around the world. LORAN is a ground-based system of receivers and

⁷Glass, Dan. The Atlantic. 13 Jun 2016. What happens if GPS fails? [Internet] [cited 2018 Apr 20]; Available from: <https://www.theatlantic.com/technology/archive/2016/06/what-happens-if-gps-fails/486824/>

⁸Timeanddate.com [Internet] How does an atomic clock work? c2018. [cited 2018 Jul 20]; Available from: <https://www.timeanddate.com/time/how-do-atomic-clocks-work.html>

⁹Department of Homeland Security. dhs.gov. [Internet] [cited 2018 Apr 22]; Available from: <https://www.dhs.gov/critical-infrastructure-sectors>

¹⁰Hawkes, Tom & McMahon, Blake. Defense One. 10 May 2017. Time warfare: threats to GPS aren't just about navigation and positioning. <http://www.defenseone.com/ideas/2017/05/time-warfare-anti-gps-arent-just-about-navigation-and-positioning/137724/>

¹¹Burke, John. DARPA. Atomic Clock with Enhanced Stability. <https://www.darpa.mil/program/atomic-clock-with-enhanced-stability>

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transmitters that was first developed during World War II. By the mid-1990s, LORAN tower networks were able to provide coverage for North America, Europe, and some other regions, primarily in the US and Canada. As GPS became available for civilian use in 1995, LORAN's popularity declined. GPS was more accurate and widely available. However, The US Coast Guard continued to work on an improved version of LORAN, called the "Enhanced" LORAN, or eLORAN. The enhanced system would be able to provide position accuracy comparable to GPS. In addition, the signal was designed to be resistant to jamming, broadcasting at hundreds of thousands of watts. Unlike GPS, eLORAN could even receive signals indoors, underwater, and in cityscapes or natural canyons or valleys.¹²

Global Networks

GPS is not the only global satellite system. The Russian high orbit satellite navigation system, called Glonass, was operational in the early 1990s. Similar to GPS, it was first intended for military use in the 1970s but later became available to civilians. Like GPS, Glonass is capable of determining an object's position using satellite signals from space. Reduction in funding after the fall of the Soviet Union caused the system to fall into disrepair. However, in the early 2000s, a federal global navigation program was adopted, allowing for Glonass to be preserved and modernized. The Russian approach was to work closely with GPS, rather than being a direct competitor. The Russians claim to have developed a chipset capable of receiving signals from GPS, Glonass, and other navigation systems. In some remote areas, it is easier to receive signals from one network than another. Commercial navigation devices for cars weren't available until 2007 and were large, expensive devices. It is thought that further development will yield improved, commercially successful devices. Military applications are still the primary focus for Glonass use, such as ballistic missile tracking.¹³

Another international satellite system called Galileo is being developed by the European Union as a civilian alternative to GPS. It is currently being testing and is expected to reach a full network of 24 satellites and six spares by 2020. The European Union has recognized the growing market for satellite navigation services and is interested in being competitive with GPS, Glonass, and the Chinese network Compass.¹⁴

¹²Glass, Dan. The Atlantic. 13 Jun 2016. What happens if GPS fails? [Internet] [cited 2018 Apr 20]; Available from: <https://www.theatlantic.com/technology/archive/2016/06/what-happens-if-gps-fails/486824/>

¹³Information and Analysis Center for Positioning, Navigation and Timing, Russia. C. 2018 [Internet] [cited 2018 Jun 20]; Available from: <https://www.glonass-iac.ru/en/guide/>

¹⁴European Commission. Growth: Internal market, industry, entrepreneurship and SMEs. C. 2018. http://ec.europa.eu/growth/sectors/space/galileo_en

Compass is currently in limited operation and is expected to be operational by 2020. Other satellite navigation systems are being developed in India and Japan.¹⁵

How GPS Could Be Disrupted

In 2012, the Department of Homeland Security (DHS) performed a GPS risk estimate. It was determined that the system's weak signals are problematic, allowing interference to happen rather easily. Disruption can originate from ground-based sources in several different ways. Possible hackers could feed incorrect data into critical resource equipment, causing power outages and location errors. Signal jammers could disable cell phone service and emergency communication, leaving fire, police, and emergency medical to conduct business using older methods. Transactions would be limited to cash, which could be difficult to access without ATM services. The longer it takes to locate the jamming devices, the more systems are affected, causing confusion and chaos.¹⁶

A more complex disruption device is called a "spoofer." Equipment in these spoofing systems produces mimicked signals that trick GPS receivers to lock onto them. The spoofed systems cause altered time and position data to be transmitted to unaware users. There is no associated alarm that indicates that anything is wrong. There has been evidence that Russia is testing a new GPS spoofing device. In 2017, the GPS on a ship in the Black Sea reported the ship's position as 20 miles inland at a nearby airport. The navigation equipment was verified as working properly. To investigate the problem, the captain contacted other nearby ships. Their GPS signals also placed them at the same airport. Although the incident has not been confirmed, it is believed that about 20 ships were affected. Experts think that this is the first known case of GPS spoofing.¹⁷

In addition to location errors, spoofing can cause communication breakdowns and market failures. It is a real threat that can be activated almost entirely with software code. It was thought that the biggest threat to GPS was jamming it by masking the satellite signal with noise. Although this can create confusion, jamming is easy to detect, causing GPS receivers to sound an alarm when the signal is lost by this method. Spoofing is a stealthier technique, generating a false signal from a ground station that mimics a real signal and fools the satellite receiver.

¹⁵GCN: Jackson, William; 12 Nov 2013. Technology, Tools and Tactics for Public Sector IT. [Internet] [cited 2018 July 03]; Available from: <https://gcn.com/articles/2013/11/12/gps-timing-position.aspx?m=1>

¹⁶Glass, Dan. The Atlantic. 13 Jun 2016. What happens if GPS fails? [Internet] [cited 2018 Apr 20]; Available from: <https://www.theatlantic.com/technology/archive/2016/06/what-happens-if-gps-fails/486824/>

¹⁷Hambling, David. New Scientist. 10 Aug 2017. Ships fooled in GPS spoofing attack suggest Russian cyberweapon. [Internet] [cited 2018 Apr 21]; Available from: <https://www.newscientist.com/article/2143499-ships-fooled-in-gps-spoofing-attack-suggest-russian-cyberweapon/>

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“Jamming just causes the receiver to die, spoofing causes the receiver to lie,” says consultant David Last, former president of the United Kingdom’s Royal Institute of Navigation.¹⁸

The US Department of Homeland Security has focused on GPS disruption for the past several years. It has listed both the intentional and unintentional threats to the satellite system. The unintentional list includes space weather, space debris, faulty software, and human error, among other things. Space weather is potentially the most devastating threat. Solar flares erupting high energy radiation from the Sun have already disabled satellites in the past. Figure 1.3 is an image of an active region on the Sun emitting a mid-level solar flare in 2014. Harmful radiation from large flares is capable of passing through the layer of the Earth’s atmosphere where GPS and communications signals travel, even though it cannot pass completely through the atmosphere to affect humans on the surface.¹⁹

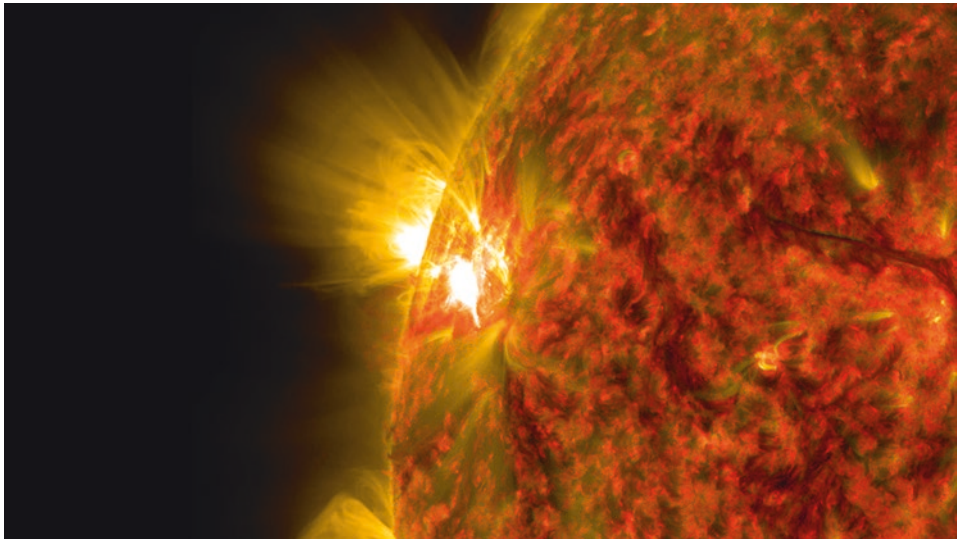


Fig. 1.3. The Sun emitting a mid-level solar flare, peaking on Nov. 5, 2014. Image Credit: *NASA/Solar Dynamics Observatory*

¹⁸Hambling, David. New Scientist. 10 Aug 2017. Ships fooled in GPS spoofing attack suggest Russian cyberweapon. [Internet] [cited 2018 Apr 21]; Available from: <https://www.newscientist.com/article/2143499-ships-fooled-in-gps-spoofing-attack-suggest-russian-cyberweapon/>

¹⁹Glass, Dan. The Atlantic. 13 Jun 2016. What happens if GPS fails? [Internet] [cited 2018 Apr 20]; Available from: <https://www.theatlantic.com/technology/archive/2016/06/what-happens-if-gps-fails/486824/>

Thus far, one approach to the prevention of GPS signal loss involves interoperability with other global navigation satellite systems such as Russia's Glonass, the European Galileo, or the Chinese Compass system. Another method involves better clocks, says Lombardi, the NIST (National Institute of Standards and Technology) metrologist, who has published numerous articles on the topic. "The typical cell tower clock has an oscillator similar to that of a wristwatch," he says, "and can drift out of tolerance in minutes without a signal." Developing better clock technology will improve a clock's resistance to drift when the signal is disrupted. Backup systems are also being developed to ensure a more robust system in case of major external disruption, both natural and unnatural.²⁰

Reflections

Today's daily activities, both civilian and military, rely on satellite networks circling the Earth. These space networks are now a critical component of the infrastructure for many commercial and military operations. Because of the nature of this technology and the fact that so many critical services are tied to its infrastructure, the GPS network has become a vulnerable target for a future attack. Among other events, there is evidence that Russia has jammed GPS reception in the Ukraine and China has hacked US weather satellites. It has become obvious that a more robust system needs to be at the center of the interconnection of resources that we rely on every day.

Few technologies have as broad an impact on both national security and our routine lifestyle as precision timing. As the US Defense Department works on new systems to counteract threats, it should keep in mind the effects of timing in modern warfare. Without deliberate, comprehensive, and coherent guidance and policy in place beforehand, we risk replacing one well-functioning but vulnerable timing component—GPS—with dozens of disparate, non-interoperable, and possibly still vulnerable timing systems.

²⁰ Glass, Dan. The Atlantic. 13 Jun 2016. What happens if GPS fails? [Internet] [cited 2018 Apr 20]; Available from: <https://www.theatlantic.com/technology/archive/2016/06/what-happens-if-gps-fails/486824/>

2

Space as the Next Theater of War

“There is no such thing as a war in space, there is just war, it’s with an adversary and if it extends into space we have to figure out how to fight it.”

—General John Hyten, head of the US Strategic Command¹

Introduction

Most of us envision a war in outer space in the same way that it is portrayed in science fiction books and popular franchises like *Star Wars*. The typical image includes a lot of space-adapted fighters and larger transport vehicles loaded with a variety of shooting weapons, particle beam weapons, and space torpedoes. Military interaction with a large celestial object such as a planet generally ends with more fancy weapons destroying a civilization or obliterating the entire object. If ever possible, we are no doubt hundreds of years away from reaching this vision of space warfare.

Still, it is important at this point in time to think about worst-case scenarios where an individual or group aims to disarm or destroy targeted satellites. Today, US satellites and outer space surveillance equipment are used for communication, military defense, and the accumulation of scientific data. While they support military activities on Earth, they do not initiate aggressive activities in outer space.

¹Villasanta, Arthur. D. 27 Feb 2017. US will fight and win a space war—and is preparing for it. [Internet] chinatopix.com. [cited 2018 April 14]. Available from: <http://www.chinatopix.com/articles/111937/20170227/will-fight-win-space-war-preparing.htm>

Other countries have demonstrated technology that could be used to disrupt satellite operations.

This chapter sets the stage for discussions on the science and technology of satellites, space sensors, and weaponry as important elements in military actions and defense.

Outer Space as a Possible Theater of War

There is no doubt that current world tensions have escalated. The increasing technological capabilities of several nations—not all friends of the United States—in the areas of nuclear weapon development, intercontinental ballistic missiles, and space satellites and their delivery systems are alarming. The number of spacefaring nations, or those capable of building and launching vehicles beyond the Earth's atmosphere, is about 14 today (Russia, US, China, UK, France, Canada, Japan, India, Israel, Ukraine, Iran, North Korea, South Korea, New Zealand), although it can be argued that the US lost its ability, at least temporarily, to travel outside of the atmosphere with the end of the Space Shuttle program in 2011.² There are a growing number of nations (over 80) that have developed satellites,³ mostly for communications purposes, utilizing other spacefaring nations to place them into orbit. There are even more nations with a growing interest in space experiments and activities to enhance their scientific knowledge.

Figure 2.1 illustrates the breakdown of the 90 known orbital launch attempts in 2017 by country. The US led the way with 32%, but Russia and China followed closely behind with 23% and 20% respectively. The new surprise entry was New Zealand, illustrating that commercial enterprise for space endeavors is sprouting up all over the globe. Most of these countries are looking to participate in outer space activities and exploration for peaceful reasons. Yet, the increasing tensions between spacefaring nations such as the US, Russia, China, Iran, and North Korea pose security threats that have prompted a shift in policy toward the use of outer space as a component in military defense. The possibility of outer space being a theater of conflict has forced the US to deliberate on how it would attempt to defend itself against intercontinental ballistic missiles loaded with weapons, or to combat aggressive acts or the use of weapons in space.

²NASA. NASA.gov. Space Shuttle Era. https://www.nasa.gov/mission_pages/shuttle/flyout/index.html

³Nwyo. [Internet]. Nwyo.com; c2018. Satellites by countries and organizations; [cited 2017 Dec 10]. Available from: <https://www.n2yo.com/satellites/?c=&t=country>

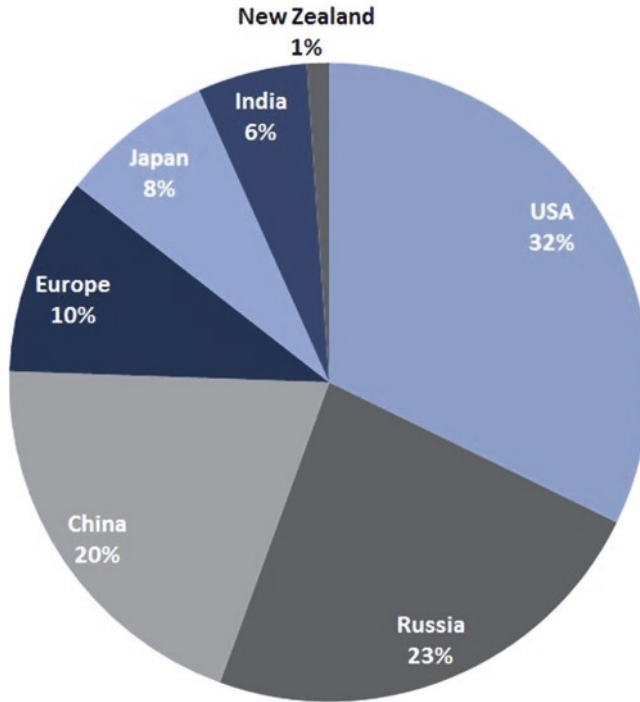


Fig. 2.1. 2017 Attempted orbital launches by country. Image Credit: [Spaceflight101.com](https://www.spaceflight101.com)

There are increasingly more warships, weapons, and ground installations armed with powerful rockets on the Earth’s surface, that, with accurate guidance, could be launched out of the atmosphere to destroy enemy spacecraft orbiting Earth. In addition, there are an increasing number of satellites in orbit, dubbed “inspection” satellites, which have the capability of following transmitted commands to track, disable, or destroy other spacecraft.⁴

It is difficult to determine how many weapons might already be in orbit. Numerous spacecraft are “dual use,” which means that they can have the potential for both peaceful functions and military applications. On command, an inspection satellite that is outwardly configured for orbital debris removal could be tasked with destroying other satellites with lasers, explosives, or simply ramming into

⁴Reuters Staff. 10 Aug 2015. When it comes to war in space, US has the edge. [Internet]. Reuters.com. [cited 2017 Dec 10]. Available from: <https://www.reuters.com/article/axe-space/column-when-it-comes-to-war-in-space-u-s-has-the-edge-idUSL1N10M2OW20150811>

them. Until the satellite attacks a target, however, it would appear to be harmless. The United States owns more space satellites than any other country, used mostly for communication or surveillance, pointed downward toward Earth's surface. A few look upward, patrolling outer space. Those are capable of tracking heat plumes from rocket launches or maneuvering spacecraft. This information can be relayed to the ground station. The US denies that any of its satellites are dual-natured or carry weapons.⁵

A military conflict in Earth orbit would severely disrupt the satellite networks that the world relies on for communication, navigation, military surveillance, and scientific research. The destruction of satellites or their ability to function could throw civilization back in time, technologically speaking. "You go back to World War Two," Air Force General John Hyten, in charge of US Space Command, said on *60 minutes*. "You go back to the Industrial Age."⁶

Conflict can occur on air, land, and sea. For the past few decades, war has had the capability to extend into outer space, beyond the Earth's atmosphere. The Outer Space Treaty of 1967, further discussed in Chap. 3 and included in Appendix A, was an international treaty agreed to by over 100 nations to formally provide guidance for the exploration and utilization of outer space, including the Moon and other celestial bodies. The treaty states that outer space should only be used for peaceful purposes. Exploration is encouraged so long as it supports the benefit and interest of all countries. Nuclear weapons or weapons of mass destruction are prohibited from being carried into outer space or placed in outer space or on a celestial body. The establishment of military bases, along with the demonstration of military activities, anywhere in space is strictly forbidden.⁷

With the expansion of business opportunities in outer space, the United States created new legislation under the Space Resource Exploration and Utilization Act of 2015. The "Space Act" addressed the country's commercial efforts to extract space resources such as precious metals from celestial bodies like asteroids.⁸ This act breaks from the 1967 treaty, which states that space exploration should benefit all nations. Under the Space Act, the specific act of mining and extracting resources

⁵Axe, David. 10 Aug 2015. When it comes to war in space, US has the edge. [Internet]. [Reuters.com](http://blogs.reuters.com/great-debate/2015/08/09/the-u-s-military-is-preparing-for-the-real-star-wars/). [cited 2017 Dec 12]. Available from: <http://blogs.reuters.com/great-debate/2015/08/09/the-u-s-military-is-preparing-for-the-real-star-wars/>

⁶Reuters Staff. 10 Aug 2015. When it comes to war in space, US has the edge. [Internet]. [Reuters.com](https://www.reuters.com/article/axe-space/column-when-it-comes-to-war-in-space-u-s-has-the-edge-idUSL1N10M2OW20150811). [cited 2017 Dec 10]. Available from: <https://www.reuters.com/article/axe-space/column-when-it-comes-to-war-in-space-u-s-has-the-edge-idUSL1N10M2OW20150811>

⁷NASA. [Internet]. nasa.gov; c2017. Outer space treaty of 1967. Last updated June 25, 2012. [cited 2017 Sep 04] Available from: <https://history.nasa.gov/1967treaty.html>

⁸Fecht, Sarah. [Internet]. popsci.com; Senate votes to legalize space mining. 11 Nov 2015. [cited 2017 Sep 5]. Available from: <https://www.popsci.com/congress-votes-to-legalize-asteroid-mining>

(including platinum and water, valuable resources in space) would solely profit US private enterprise. The bill states that “any asteroid resources obtained in outer space are the property of the entity that obtained such resources, which shall be entitled to all property rights thereto.”⁹ The legislation is meant to incentivize and promote the growth of the private space industry, separate from the national government program.

Due to the changing political, economic, and technical climate of the past few years, the treaty of 1967 has drawn a substantial amount of scrutiny. Originally, only the US and Russia were able to place spacecraft into orbit and to explore outer space. There are now several countries that possess the capabilities or have plans that either violate the treaty or challenge its generalized language concerning the purpose of space exploration and the weaponization of space.

The 1991 Gulf War, when US led troops drove the Iraqi out of Kuwait, was the first demonstration of the use of outer space for military purposes. Although the conflict didn’t occur in outer space, it has been referred to as the “first space war.” The reason for this designation is that the US and coalition forces relied heavily on GPS (Global Positional System) satellites and other types of satellite capabilities to manage and control the military conflict and navigate civilian activities.¹⁰

The fleet of Navstar GPS satellites reside in a medium Earth orbit at an altitude of approximately 12,550 miles. Figure 2.2 depicts a network of GPS satellites. The orbits of GPS satellites are tilted from the Earth’s equator by about 55°. The configuration ensures that at least four satellites are observable at least 15° above the horizon at any given time anywhere in the world. Each satellite circles the Earth twice a day.¹¹ A satellite in a circular geosynchronous orbit directly over the equator will have a geostationary orbit that does not move relative to the ground. Satellites in geostationary orbit directly above the equator rotate at the same velocity as the Earth, continuously staying above the same spot. Because of the position’s unique qualities, this is a preferred orbit for surveillance, communication, and weather satellites.¹²

⁹Congress. [Internet]. [Congress.gov](https://www.congress.gov/bill/114th-congress/house-bill/2262); c2017. H.R.2262—US commercial space launch competitiveness act 114th congress (2015–2016). [cited 2017 Sep 10] Available from: <https://www.congress.gov/bill/114th-congress/house-bill/2262>

¹⁰Anson, Peter and Cummings, Dennis. “The First Space War: the contribution of Satellites to the Gulf War,” *RUSI Journal* 136 (1991): pp. 45–53.

¹¹Howell, Elizabeth. [Space.com](https://www.space.com/19794-navstar.html). 26 Apr 2018. Navstar: GPS Satellite Network. [Internet] [accessed 8 jul 2018] Available from: <https://www.space.com/19794-navstar.html>

¹²[NASA.gov](https://earthobservatory.nasa.gov/Features/OrbitsCatalog/page2.php). 04 Sept 09. Earth Observatory. Three Classes of Orbits. [Internet] [accessed 8 jul 2018] Available from: <https://earthobservatory.nasa.gov/Features/OrbitsCatalog/page2.php>

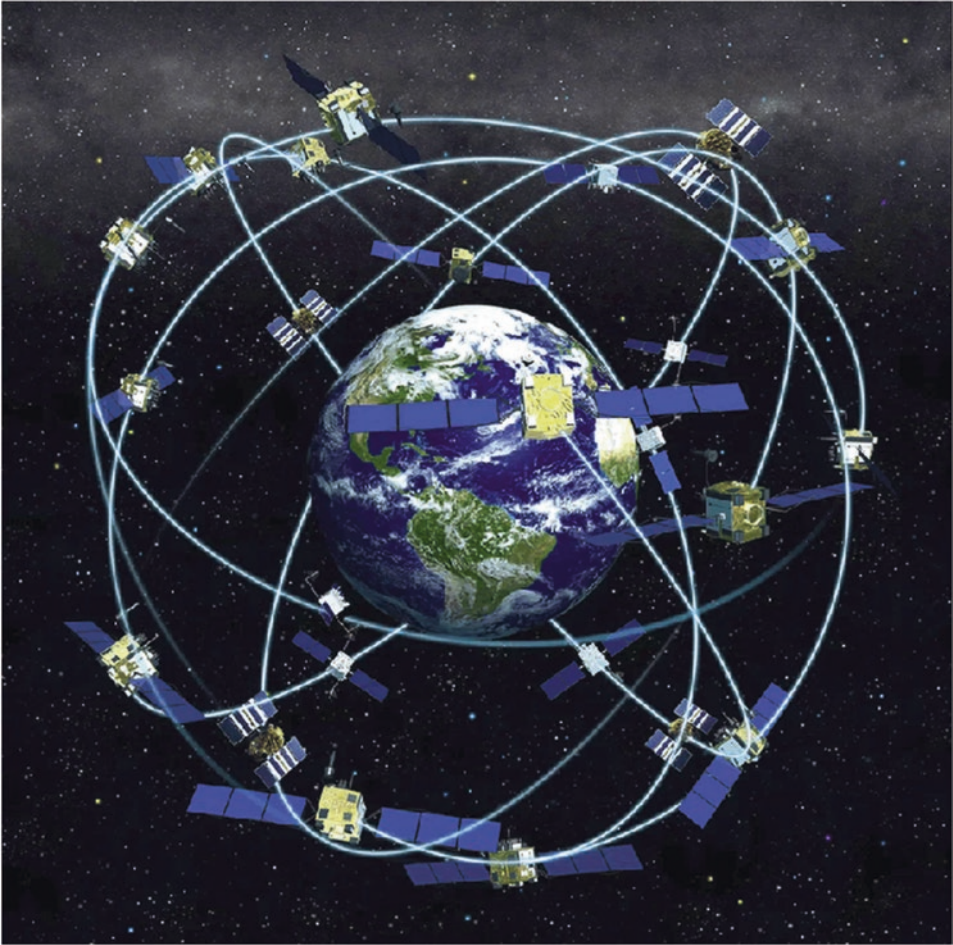


Fig. 2.2. A network of GPS satellites with orbits inclined to the Earth's equator by about 55° . Image Credit: NOAA

Over the years, the world has become dependent on the capabilities of the satellites in orbit. As modern militaries and the world's economy rely more and more on satellite support, countries now have a high priority to protect these orbiting assets. It is likely that a conflict between space capable nations will involve a battle thousands of miles above Earth's surface.

Over the past few years, the three world superpowers, the United States, Russia, and China, have been steadily increasing their space-based weapon capabilities, focusing primarily on satellite defense technology. The following is a summary of the efforts of these three powers.

China

China's space program, although slow to develop compared to the US and Russia, is now in a regional space race in Asia. China became the third nation after Russian and the US to launch a human spaceflight, a major accomplishment that took place in 2003.¹³ Asia's booming economy has infused resources into China's space program and military efforts. Primarily, China's desire for regional dominance in space is driven by its desire for regional dominance—bringing prestige to the nation and fostering the development of science and technology.¹⁴

A major focus of China has been exploring the Moon. China has launched several types of vehicles to the Moon in the past decade to orbit and explore the body's surface. A series of Chang'e spacecraft (1–3) missions were successfully conducted. In 2013, the Chang'e 3 rover landed on the Moon's surface, making China the third nation after US and Russia to accomplish the feat of a soft landing on the lunar surface (Fig. 2.3).¹⁵ The Chang'e 4 and 5 spacecraft will both investigate the dark side of the Moon. It is anticipated that an operation to land a craft on



Fig. 2.3. Illustration of Chinese rover on the Moon. Image Credit: ESA/CSNA

¹³ Staff. [Internet]. [Space.com](https://www.space.com/1616-making-history-china-human-spaceflight.html). Making history: China's first human spaceflight; 28 Sept 2005 [cited 2017 Sept 20]; Available from: <https://www.space.com/1616-making-history-china-human-spaceflight.html>

¹⁴ Dawson, Linda. *The Politics and Perils of Space Exploration*. Springer Nature, 2017

¹⁵ Staff. [Internet]. [Space.com](https://www.space.com/23968-china-moon-rover-historic-lunar-landing.html). China lands on the moon: historic robotic lunar landing includes first Chinese rover. 14 Dec 2013 [cited 2018 Jun 20]; Available from: <https://www.space.com/23968-china-moon-rover-historic-lunar-landing.html>

the dark side will be tried before 2020, an achievement that no other country has attempted so far.¹⁶

As stated, China has some of the most technologically ambitious plans to orbit and land humans back on the Moon. It even has plans to possibly set up a colony on the surface. In addition, China plans to go to Mars by the 2020s. “Our long-term goal is to explore, land, and settle [on the Moon],” Wu Weiren, chief designer of Mars and China’s Moon missions, said in a video interview with BBC. “We want a manned lunar landing to stay for longer periods and establish a research base.”¹⁷

China’s ambitious lunar plans have led some to be concerned that China’s advancements could be converted into control over resources found on the Moon, replenishing some of Earth’s resources. The Moon has a wealth of rare minerals and precious metals that yield high prices and are commonly used in electronic and industrial applications. As an example, the lunar soil is rich in helium-3, an element rarely found on Earth. Helium-3 can be used to generate nuclear power without creating radioactive waste.¹⁸

China continues to expand its space activities, including plans to construct a large space station, a new launch complex, and more powerful boosters, and to develop complex robotic missions to the Moon and Mars.¹⁹

Other nations might have viewed China’s space plans as peaceful, if it weren’t for an aggressive move made in a 2007 missile test conducted in low Earth orbit (LEO) approximately 500 miles above Earth. The test destroyed one of China’s own old model weather satellites and created more than 3000 pieces of space junk.²⁰ After this event, the Chinese government said it would not perform additional tests, yet comparable tests were carried out only a few years later in 2010 and 2013 under the guise of missile defense. The 2013 test reached an altitude of 18,600 miles, close to geosynchronous orbit (22,236 miles), where most of the

¹⁶ Staff. [Internet]. [Space.com](http://www.space.com). Chang’e-4: visiting the far side of the moon; 25 May 2018 [cited 2018 Jun 20]; Available from: <https://www.space.com/40715-change-4-mission.html>

¹⁷ Harrington, Rebecca. Tech Insider. China plans to reach Mars by 2020 and eventually build a moon base. Apr. 21, 2016 <http://www.businessinsider.com/china-plans-mars-moon-landings-2016-4>

¹⁸ Moon potential goldmine of natural resources July 16, 2009 by Jean-Louis Santini <https://phys.org/news/2009-07-moon-potential-goldmine-natural-resources.html>

¹⁹ David, Leonard. [Space.com](http://www.space.com). 03 Dec 2014. China Has Big Plans to Explore the Moon and Mars. [Internet] [cited 09 Jul 2018] Accessed from: <https://www.space.com/27893-china-space-program-moon-mars.html>

²⁰ Shalal-Esa, Andrea. Reuters World News. 13 Jan 2013. China’s space activities raising U.S. satellite security concerns. [Internet] [cited 09 Jul 2018] Accessed from: <https://www.reuters.com/article/us-china-usa-satellites/chinas-space-activities-raising-u-s-satellite-security-concerns-idUSBRE90D08620130114>

United States ISR (Intelligence, Surveillance, and Reconnaissance) satellites are located. In 2015, China tested its exoatmospheric vehicle, reportedly able to destroy US satellites. Chinese press reports said the test was a missile defense interceptor flight test. It is thought that the missile tested had onboard capabilities to ram into satellites and destroy them.²¹

China's anti-satellite test conducted in 2007 was perceived as an aggressive act against the United States and a possible violation of the Space Treaty. The satellite systems orbiting the Earth are critical components of the national security for US and other nations, including Europe and Russia. China's proven capability to destroy a satellite in orbit by launching an interceptor in 2007 raised concerns over the security of assets in outer space. It also generated alerts regarding the possible damage or destruction of property from high velocity space debris produced from this type of collision. This event, as well as China's following actions, represent a pattern of aggression that the world is closely watching.²²

In 2016, China launched the Aolong-1 spacecraft, which it claims is tasked with cleaning up manmade debris in space, otherwise known as space junk. However, other reports indicate that the spacecraft is a dual-use ASAT weapon. This technology can be used to target and approach foreign satellites, deliberately disabling them without necessarily destroying them. The ability to use these assets for communications and intelligence gathering could be temporarily or permanently affected.²³

Co-orbital anti-satellite systems are armed with an onboard weapon such as an explosive charge, kinetic energy weapon, laser, jammer, or even a robotic arm. The ASAT vehicle is launched into the same orbit as a target satellite and then moves in close to the spacecraft. In addition to physical destruction, China is also testing soft-kill methods (interrupt operations electronically) to disable a satellite, or even grab onto it. China has also acquired and developed a number of satellite jammers on ground bases since the mid-2000s. These jammers are designed to disrupt satellite communications by interfering or scrambling signals being transmitted or received. Finally, since the 1990s, China has also committed resources to the research and development of directed energy weapons. The highly focused directed energy lasers can interfere or destroy spacecraft.²⁴

²¹ Branigan, Tania. The Guardian. 12 Jan 2010. China successfully tests missile interceptor. [Internet] [cited 09 Jul 2018] Accessed from: <https://www.theguardian.com/world/2010/jan/12/china-tests-missile-interceptor>

²² Asia's space plans worry. Eastern Eye. 2013 Dec 20;Sect. 17.

²³ Staff. [Internet] Spaceflight 101: China's new orbital debris cleanup satellite raises space militarization concerns. [cited 2018 Jan 5]. <http://spaceflight101.com/long-march-7-maiden-launch/aolong-1-asat-concerns/>

²⁴ Vasani, Harsh. The Diplomat. 19 Jan 2017. How China is weaponizing outer space. [Internet] [cited 2018 Jan 3]. Available from: <https://thediplomat.com/2017/01/how-china-is-weaponizing-outer-space/>

According to a 2015 RAND report, spaced-based operations would be a critical component of an armed conflict between the United States and China. The report states that China has invested in advanced space technology with capabilities in “satellite communication (SATCOM), intelligence, surveillance, and reconnaissance (ISR), satellite navigation (SATNAV), and meteorology, as well as manned, unmanned, and interplanetary space exploration.” In addition, China has developed the technology to control or disable the use of space-based assets by enemy nations in a conflict, including the “development of directed-energy weapons and satellite jammers.”²⁵ China’s interest and development of ASAT weapons can be interpreted as a practical approach for regional security and influence. Still, China is surely aware of the US’s dependence on its space assets. Its development of long-range missiles and weapons threatens such resources.²⁶

Russia

Russia’s history and experience in space exploration is very different from China’s, due to its central role in the twentieth century Cold War with the US. Even after the Cold War, Russia had a robust space program that included missile and rocket development, space station deployment, space transport, and deep space exploration. Future plans are extensive and include similar developments as China in ASAT missile testing and journeys to the Moon and Mars, setting up landing bases, and more.

The Russian Federal Space Agency, Roscosmos, has played a significant role in maintaining the International Space Station (ISS). After the Space Shuttle program was terminated in 2011, in a controversial move, Russia started ferrying both American astronauts and Russian cosmonauts to the ISS. The cost per astronaut for this service has skyrocketed to over \$80 million per seat. The once-Cold War enemies and competitors in the Space Race were teaming together to solve the US transportation problem. However, recently, the US-Russia relations have once again become tense, and the US is shifting back to greater independence from the Russian transport services through its own Commercial Crew Transport program.²⁷

²⁵ Rand report. The US—China military scorecard: forces, geography, and the evolving balance of power. 1996–2017. RAND corporation; 2015. pp. 227–244.

²⁶ Rand report. The US—China military scorecard: forces, geography, and the evolving balance of power. 1996–2017. RAND corporation; 2015. pp. 227–244.

²⁷ CBS/AP. 06 Aug 2015. NASA: Seats on Russian rockets will cost U.S. \$490 million. [Internet] [cited 09 Jul 2018] Accessed from: <https://www.space.com/16748-international-space-station.html>

22 Space as the Next Theater of War

The relationship between the two superpowers is complicated, and the two space programs have become intertwined in a myriad of ways. In 2016, there was a Senate floor debate about the National Defense Authorization Act over whether or not the Department of Defense would be allowed to continue using Russian rocket engines to lift national security satellites into orbit. The engines, called RD-180s, provide first-stage thrust for Atlas launch vehicles built by United Launch Alliance, or ULA (see Fig. 2.4), a joint venture of Boeing and Lockheed Martin. ULA had a monopoly on Pentagon launches until 2015, when the Air Force certified Elon Musk's SpaceX as a competing provider of launch services to the military. Russia's continuous military provocations convinced many legislators that Russian engines needed to be removed from the US military space program as soon as possible. If Russian engines were banned, then ULA would be unable to use Atlas for military launches. Its other launch vehicle, Delta, costs about 35% more than Atlas and so has no hope of beating SpaceX's Falcon 9 launch vehicle in a price-based competition.

The Senate approved an amendment to the authorization bill that would allow use of up to 18 more RD-180 engines through the end of 2022. The House had already voted on a bill that would allow further use of the Russian engines, so the debate was over and ULA won. The idea of relying on Russian engines to transport security-sensitive, intelligence-gathering satellites and American astronauts into space might seem outrageous, but SpaceX at the time was not capable of lifting heavy satellites into high orbits, and the Atlas was the cheapest option to



Fig. 2.4. Atlas rocket launching using Russian engines to lift off. Image Credit: *US Air Force*

accomplish the job. If SpaceX's lobbying campaign had succeeded, Musk's company would have ended up with a monopoly on nearly any military payload it was capable of lifting into orbit.²⁸

Russia has excelled in rocket design and development since the early years of the Space Race. Recently, however, engine reliability issues and the high cost of launching payloads, combined with the mismanagement of money, have put the Russian space industry in financial straits. The construction of a new launch facility is being held up due to funding delays and possible corruption. The Federal Space Agency's budget has been reduced by 35% for the next decade.²⁹ Igor Komarov, the head of Roscosmos, said at a news conference in 2015, "The cost of the program's projects has undergone significant changes over the last year, given the prevailing economic conditions, changes in exchange rates, and changes in the level of inflation."³⁰

One of the Russian plans on the horizon includes the design of a space station that expands on ISS technology. Former Roscosmos director and commander of the Russian Space Forces, Oleg Ostapenko, says, "We are considering the possible construction of a high-latitude station from which 90% of the Russian territory will be visible. It may become a base for prospective lunar expeditions."³¹ Roscosmos is also developing a new manned spacecraft that will haul crews and supplies to the ISS.³² More advanced missions planned for an expedition to Mars and the establishment of a lunar base are well into the future by some 20–30 years. Their progress also relies on a steady funding level.

Russia has been active in developing anti-satellite defense technologies, successfully testing its PL-19 Nudol missile for the fifth time in 2016. Its reasoning is the same as the US and China: to protect assets in outer space that are vital for the military and communications. There is speculation that Russia may have also developed satellites capable of disabling other satellites using the ramming technique.³³

²⁸Thompson, Loren. Forbes. 7 Jul 2016. Why SpaceX lost its bid to ban Russian rocket engines. [Internet] [cited 2018 Jan 10]. Available from: <https://www.forbes.com/sites/lorenthompson/2016/07/07/why-spacex-lost-its-bid-to-ban-russian-rocket-engine-debate/#3990a47c5f52>

²⁹Kottasova, Ivana. Economic crisis at heart of Russia's pride: its space program. 27 April 2015. [Internet] [cited 2016 Jan 16]. Available from: <http://money.cnn.com/2015/04/27/news/economy/russia-space-crisis-cosmodrome/>

³⁰Kottasova, Ivana. Economic crisis hits at heart of Russia's pride: its space program. CNN Money (London). 27 April 2015. [Internet] [cited 2015 June 15]. Available from: <http://money.cnn.com/2015/04/27/news/economy/russia-space-crisis-cosmodrome/>

³¹Roscosmos: High-latitude orbital station may become lunar expeditions' base. Interfax: Russia & CIS General Newswire. 16 Dec 2014.

³²Russian News Agency. Russia's new manned spacecraft to be 3.5 times cheaper than US Dragon. 22 Jan 2016. [Internet] [cited 2017 June 16]. Available from: <http://tass.ru/en/science/851562>

³³Williams, Weston. Russia launches anti-satellite weapon: a new war front in space? Christian Science Monitor. 22 Dec 2016. [Internet] [cited 2017 June 16]. Available from: <https://www.csmonitor.com/USA/Military/2016/1222/Russia-launches-anti-satellite-weapon-A-new-warfront-in-space>

Russian President Vladimir Putin in 2017 called for improving the national defense by expanding space technologies to the development of ballistic missile launch sensing satellites. He called to have at least 15 of these satellites in orbit by 2020. He also stated that Russia is prepared to work with foreign companies to purchase additional satellites as well as to acquire sensing data accessed from non-Russian orbital craft.³⁴

Recent Russian military developments reflect the continued importance of dominance in outer space. The nation's focus is on creating advanced technologies and developing weapons to match what China and the US are perceived to be testing for military operations in space. It is difficult to know with certainty exactly what Russia is developing for future use in space. One example of operations cloaked in secrecy is the mysterious story of three Russian satellites launched into low Earth orbit in 2013. The satellites were designated as service spacecraft, with applications to refuel or clean up debris. However, nobody knows what these satellites are capable of or what the focus of their mission is. They remained dormant for years until they were recently revived—Kosmos 2491, 2499, and 2504. In 2017, they were spotted moving in an unpredictable pattern. It is thought that the Russians were testing the satellites' anti-satellite (ASAT) ability to scan or match a target satellite's orbit and approach and interact with it.³⁵

Over 50 years ago in 1963, the Soviet Union launched its prototype of the "killer" satellite, what we call today an anti-satellite system (ASAT). The vehicle would approach the targeted satellite and destroy it with shrapnel type material. Secret flight tests of killer satellites continued through the 1960s. In 1968, the USSR successfully intercepted and destroyed a target satellite in orbit. However, it would take until 1991 before the ASAT system became fully operational. An upgraded ASAT system, codenamed IS-MU, had the capability of chasing enemy satellites even if the target used evasion maneuvers. Shortly after it was declared operational, as the Cold War was winding down, Russian President Boris Yeltsin ended the program in order to save money.³⁶

About a decade later, in the 2000s, the United States and China demonstrated their own capabilities to attack and destroy satellites in space. To counteract their efforts, the Russian ASAT program resurfaced. The Russian military began a lower cost system that consisted of converted ballistic missiles equipped with

³⁴ Kremlin events. [Internet] [cited 2017 Dec 16]. Available from: <http://en.kremlin.ru/events/president/news/54539>

³⁵ Simha, Rakesh Krishnan. How Russia's sleeping satellites could wreak havoc on the west. *Russia Beyond*. 25 May 2017. [Internet] [cited 2017 Dec 16]. Available from: <https://www.rbth.com/defence/2017/05/25/russias-sleeping-satellites-wreck-havoc-on-the-west-769276>

³⁶ Zak, Anatoly. The hidden history of the soviet satellite-killer. *Popular Mechanics*. 1 Nov 2013. [Internet] [cited 2017 Dec 20]. Available from: <http://www.popularmechanics.com/space/satellites/a9620/the-hidden-history-of-the-soviet-satellite-killer-16108970/>

armed satellites capable of colliding with enemy satellites. In January 2010, the Roscosmos director Ostapenko reported that Russia was developing ways to respond to threats from space. “The USSR was developing inspection and strike spacecraft,” Ostapenko said. “Our policy—there should be no war in space, but we are military people and should be ready for everything. Our activities in this direction would be dependent on others, but, trust me, we would be able to respond quickly and adequately.”³⁷

Throughout history, it is obvious that the Kremlin closely associates its military use of outer space with the advancement of missile defense systems by the United States. From the Cold War era through the past decades, Russia’s moves have generally been in step with the US, in order to keep up with crucial technological developments for a global strike system.

Because of their early start, Russia had a lead in ASAT development. Its present-day satellites are likely more advanced and able to interfere or permanently disrupt an enemy satellite’s electronics, in particular GPS signals. As of late 2017, Russia has the third largest satellite constellation in the world—134—with the US at 579 and China at 192. If one combines the European Union satellites together (218 satellites), Russia’s constellation is classified fourth. One hundred and fifty one military satellites belong to the US, 81 to Russia, and 58 to China.³⁸

Russia has historically promoted open discussions about the military use of outer space on a global stage. The draft Treaty on Prevention of the Placement of Weapons in Outer Space and of the Threat or Use of Force against Outer Space Objects (PPWT) were both introduced to the Conference on Disarmament (CD) by Russia and China in 2008. The proposal was met with opposition by the international community and specifically the United States, who saw the treaty as an unverifiable restriction of its options in space. The US Office of Science & Technology Policy 2006 states that:

“The United States will oppose the development of new legal regimes or other restrictions that seek to prohibit or limit US access to or use of space. Proposed arms control agreements or restrictions must not impair the rights of the United States to conduct research, development, testing, and operations or other activities in space for US national interests.”³⁹

³⁷Zak, Anatoly. The hidden history of the soviet satellite-killer. Popular Mechanics. 1 Nov 2013. [Internet] [cited 2017 Dec 20]. Available from: <http://www.popularmechanics.com/space/satellites/a9620/the-hidden-history-of-the-soviet-satellite-killer-16108970/>

³⁸Luzin, Pavel. Space power: what is Russia’s military strategy in outer space? The Intersection Project: Security. 25 Oct 2017. [Internet] [cited 2017 Dec 22]. Available from: <http://intersectionproject.eu/article/security/space-power-what-russias-military-strategy-outer-space>

³⁹Jaramillo, Cesar. In defence of the PPWT treaty: toward a space weapons ban. Project Ploughshares. 2009 Vol. 30 Issue 4. [Internet] [cited 2017 Dec 23]. Available from: http://ploughshares.ca/pl_publications/in-defence-of-the-ppwt-treaty-toward-a-space-weapons-ban/

The governments of Russia and China presented an updated version of their draft PPWT in 2014. At that time, they included the following explanation: “We consider a legally binding ban on placement of weapons in outer space as one of the most important instruments of strengthening global stability and equal and indivisible security for all.”⁴⁰ Even the most current draft treaty does not address ASAT systems or soft-kill weapons such as lasers that could be used to temporarily or permanently incapacitate a satellite (see Fig. 2.5). Nor does the latest draft address technological advances such as co-orbital or direct-ascent weapons (like ground-based missiles that target space assets, as did the Chinese ASAT test in 2007). Finally, the draft treaty does not address space debris or its removal, even though these issues will likely cause a significant challenge in outer space equivalent to space-based weapons.⁴¹ Unless the US alters its space policy, the future of the PPWT remains questionable.

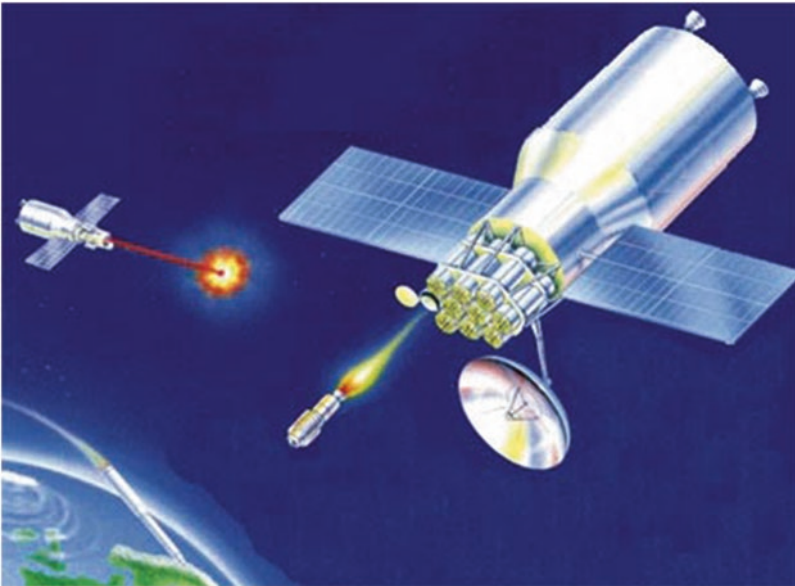


Fig. 2.5. The 2014 China-Russia treaty proposal would ban the placement of weapons in outer space, but it doesn’t address ground-based weapons that could destroy satellites. Image Credit: *US Defense Department*

⁴⁰ Listner, Michael and Rajagopalan, Rajeswari Pillai. The 2014 PPWT: a new draft but with the same and different problems. *The Space Review*. 11 Aug 2014. [Internet] [cited 2017 Dec 23]. Available from: <http://www.thespacereview.com/article/2575/1>

⁴¹ Listner, Michael and Rajagopalan, Rajeswari Pillai. The 2014 PPWT: a new draft but with the same and different problems. *The Space Review*. 11 Aug 2014. [Internet] [cited 2017 Dec 23]. Available from: <http://www.thespacereview.com/article/2575/1>

In late 2016, Russia tested what was thought to be an ASAT weapon, according to US sources that tracked the weapon. The weapon did not create debris, indicating it did not destroy a target. The Russian test came just as President-elect Donald Trump prepared to enter the White House and could be regarded as a demonstration of Moscow's capability in space.

The most vital communications and navigation satellites orbit at an altitude of tens of thousands of miles above the Earth's surface, and, most likely, intercontinental ballistic missiles would be needed to destroy them. However, Moscow could demonstrate its prowess by destroying a low Earth-orbiting satellite in a similar way to how the US destroyed a descending satellite using a ballistic missile system in 2008.⁴²

While Russia is involved in talks over the demilitarization of outer space, it continues to invest in ground facilities to control a satellite's orbit and to conduct electronic warfare by targeting space navigation and communications systems.⁴³ Time will tell how this story unfolds. According to Sputnik News, US Air Force Gen. John E. Hyten suspects that China and Russia have developed the technology necessary to target military space-based assets, including jamming and laser weapons. Hyten said at the 2017 Reagan National Defense Forum:

"Our adversaries have been watching us ever since the first Gulf War... The Chinese and the Russians, in particular, for the last twenty plus years have been watching what we have been doing and developing, and they have not been secret about it. They have been... testing weapons, building weapons to operate from the earth in space—jamming weapons, laser weapons, and they have not kept it secret."⁴⁴

According to the general, Russia and China were ostensibly building those competencies to "change the balance of power in the world" and to challenge the United States. In addition, Hyten pointed out that there are currently no defined rules of engagement for military conflicts in space and any standard international rules would be difficult to monitor.⁴⁵

⁴² Sciutto, Jim and Starr, Barbara. Sources: Russia tests anti-satellite weapon. 21 Dec 2016. [Internet] [cited 2018 Jan 4]. Available from: <https://www.cnn.com/2016/12/21/politics/russia-satellite-weapon-test/index.html>

⁴³ Sciutto, Jim and Starr, Barbara. Sources: Russia tests anti-satellite weapon. 21 Dec 2016. [Internet] [cited 2018 Jan 4]. Available from: <https://www.cnn.com/2016/12/21/politics/russia-satellite-weapon-test/index.html>

⁴⁴ Sputnik News. US gen. alleges Russia, China building weapons against military assets in space. 12 Mar 2017. [Internet] [cited 2018 Jan 4]. Available from: <https://sputniknews.com/military/201712031059654917-us-general-weapons-russia/>

⁴⁵ Sputnik News. US gen. alleges Russia, China building weapons against military assets in space. 12 Mar 2017. [Internet] [cited 2018 Jan 4]. Available from: <https://sputniknews.com/military/201712031059654917-us-general-weapons-russia/>

The United States

The United States' historical development of ballistic missile defense and outer space satellite technologies is detailed in Chap. 3. However, as a comparative summary to China and Russia, it is important in this section to identify the US's new and more advanced technology and weaponry in space.

In 1985, the United States launched its final Cold War ASAT missile, tested aboard a vertically flying F-15 fighter (shown in Fig. 2.6).⁴⁶ For the following three decades, Russia and the US did not outwardly test or participate in the



Fig. 2.6. An anti-satellite missile launched from a highly modified F-15A over Edwards Air Force Base, California, September 18, 1985. Image Credit: *US Air Force*

⁴⁶ [Aviation.com](https://www.livescience.com/4832-satellite-22-years.html) staff. How to down a satellite: go back 22 years. *Livescience*. 20 Feb 2008. [Internet] [cited 2018 Jan 5]. Available from: <https://www.livescience.com/4832-satellite-22-years.html>

militarization of outer space. In 2002, President George W. Bush removed the United States from a treaty with Russia that would prohibit the development of antiballistic-missile weapons. The reasoning was to protect the US from nuclear attack by rogue enemy states such as North Korea. In addition, this allowed the US to deploy interceptor missiles. However, withdrawing from the treaty also questioned the earlier 1967 agreement addressing the peaceful use of space.⁴⁷

As noted earlier, 5 years after this incident in 2007, China destroyed one of its own old satellites with a rocket launched from a ground site in a test of a basic anti-satellite system. The explosion spread thousands of potentially hazardous pieces of debris across low orbits, thereby accelerating the militarization of space. The United States took this as an opportunity to expand its weapon arsenal in Earth orbit. The US military's Advanced Technology Risk Reduction spacecraft, launched into an 800-mile-high orbit in 2009, hosts an infrared camera capable of detecting the heat trails from rocket launches and probably other spacecraft. The spacecraft can then transmit detailed tracking data to human operators at a ground base. The risk-reduction satellite works in combination with other spacecraft and Earth-based sensors in order to keep track of over 1000 active satellites.

The Space-Based Space Surveillance satellite, a telescope-like spacecraft launched in 2010, "has a clear and unobstructed view," according to an Air Force fact sheet, "of resident space objects orbiting Earth from its 390-mile-altitude orbit." The term "resident space object" is military lingo for satellites. A network of ground radars and telescopes supplements the orbital sensors. Observing and tracking other countries' satellites is passive and thus considered peaceful. The US military also operates spacecraft that are capable of maneuvering close to enemy satellites in order to inspect, interfere, or damage them.⁴⁸

Another type of spacecraft that could either be used as a weapon or to carry weapons to Earth orbit is the US Air Force X-37B space plane (see Fig. 2.7), first launched in 2010. The vehicle is a quarter size version of the Space Shuttle, boosted into low orbit on top of a rocket but landing back on Earth like an airplane. The Air Force describes these maneuverable mini-shuttles as being part of "an experimental test program to demonstrate technologies for a reliable, reusable, unmanned space test platform." In reality, the X-37B could also be used to attack other spacecraft. However, the mini-shuttles are limited to low orbits, whereas other maneuverable satellites are capable of higher orbits, making them better at "inspecting" and following enemy spacecraft.⁴⁹

⁴⁷Neilan, Terence. Bush pulls out of ABM treaty; Putin calls move a mistake. 13 Dec 2001. New York Times [Internet] [cited 2018 Jan 6]. Available from: <http://www.nytimes.com/2001/12/13/international/bush-pulls-out-of-abm-treaty-putin-calls-move-a-mistake.html>

⁴⁸Axe, David. US has the edge in 'war in space'. Arab Times. 13 Aug 2015. Accessed 2018 Jan 7: <http://www.arabtimesonline.com/wp-content/uploads/pdf/2015/aug/13/18.pdf>

⁴⁹Axe, David. US has the edge in 'war in space'. Arab Times. 13 Aug 2015. Accessed 2018 Jan 7: <http://www.arabtimesonline.com/wp-content/uploads/pdf/2015/aug/13/18.pdf>

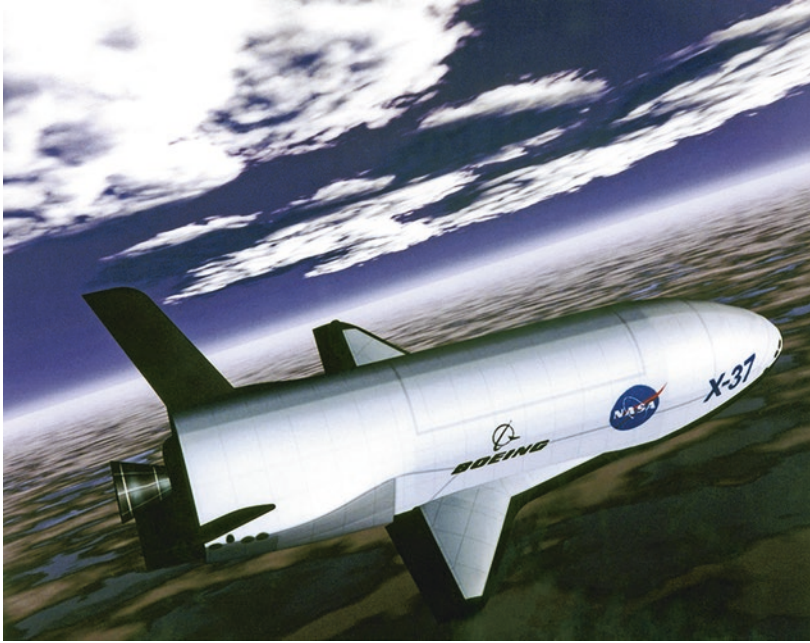


Fig. 2.7. An artist's conception of the X-37 Advanced Technology Demonstrator as it glides to a landing on earth. Image Credit: NASA

The Microsatellite Technology Experiment (MiTEx) satellites, which the military launched into low Earth orbit in 2006, are examples of US maneuverable satellites. The MiTEx satellites are small, weighing just 500 pounds each. This makes them harder for enemy sensors to detect. In orbit since 2014, the Geosynchronous Space Situational Awareness Program satellites are much bigger and are in stationary GPS positions 22,000 miles above Earth. They are capable of monitoring other satellites and can, according to the Air Force, “maneuver near a resident space object of interest, enabling characterization for anomaly resolution and enhanced surveillance.”⁵⁰

In 2008, the US Navy cruiser Lake Erie, which was equipped with an advanced radar, launched a modified antiballistic-missile interceptor. The rocket hit a non-working satellite at an estimated velocity of 22,000 mph (35,405 kph), demolishing it. Today, the United States has dozens of warships carrying hundreds of the same SM-3 missiles, sufficient numbers to destroy a large portion of satellites kept by Russia and China in low orbit.⁵¹

⁵⁰ Axe, David. US has the edge in ‘war in space’. Arab Times. 13 Aug 2015. Accessed 2018 Jan 7: <http://www.arabtimesonline.com/wp-content/uploads/pdf/2015/aug/13/18.pdf>

⁵¹ Axe, David. US has the edge in ‘war in space’. Arab Times. 13 Aug 2015. Accessed 2018 Jan 7: <http://www.arabtimesonline.com/wp-content/uploads/pdf/2015/aug/13/18.pdf>

After the Chinese ASAT tests, the United States realized that crucial national security satellites parked in geostationary earth orbit were well within the reach of its competitors. As a response, in 2015 the Pentagon announced the launch of a “Space War Center” to counter threats from China and Russia in space, part of a \$5 billion boost in space security spending for the Department of Defense. Yet, over 3 years later, not much has developed following the creation of this center.⁵²

The United States wants to ensure that outer space stays peaceful instead of transforming into a military battleground. China and Russia have been advocating for a debate on a Prevention of an Arms Race in Outer Space (PAROS) treaty, which would prohibit outer space weaponization and the use of outer space for aggressive military actions. Russia and China have also submitted a draft treaty to the UN preventing weapons from being positioned in outer space.⁵³ Most likely, the United States will not want to agree to an arms-control treaty if it means restricting the US National Missile Defense system. The US withdrew from the Anti-Ballistic Missile Treaty in 2001 and went on to develop ground- and sea-based missile defenses capable of acting as ASAT weapons.⁵⁴ Now the United States is going even further as it considers breaking away from the Outer Space Treaty of 1967 in order to prepare for the possibility of arming satellites or other space vehicles with weapons for security purposes.

Reflections

Outer space is still seen as the next great area for humans to explore. Our manned missions to the Moon and our presence in low Earth orbit are a very small step to exploring the vast universe. Unmanned probes explore the outer reaches of the Solar System, reporting back scientific findings. In the midst of peaceful space exploration is the undercurrents of competition between nations and a sense that pristine celestial bodies can be exploited for power or monetary value.

Many US space missions have had a dual purpose: the peaceful accumulation of scientific data to benefit all of humanity, and the use of space and its objects to gain an upper hand on enemy activities and even set up covert military operations.

⁵² Vasani, Harsh. The Diplomat. 19 Jan 2017. How China is weaponizing outer space. [Internet] [cited 2018 Jan 3]. Available from: <https://thediplomat.com/2017/01/how-china-is-weaponizing-outer-space/>

⁵³ NTI. Proposed Prevention of an arms race in space (PAROS) treaty. 29 Sep 2017. [Internet] [cited 2018 Jan 5]. Available from: <http://www.nti.org/learn/treaties-and-regimes/proposed-prevention-arms-race-space-paros-treaty/>

⁵⁴ Arms Control Association. Aug 2002. [Internet] [cited 2018 Jan 3]. Available from: https://www.armscontrol.org/act/2002_07-08/abmjul_aug02

32 **Space as the Next Theater of War**

It is not surprising that other spacefaring nations have similar dual-use missions in order to keep up with the changing nature of space applications and to maintain power and security.

It is clear from the complex, aggressive activities of China, Russia, and the US that such nations must find better solutions to uphold their security and defense at the same time that they protect global scientific discovery and space exploration of the worlds beyond.



The Environment of Space as a Theater of War

“War and space exploration are alternative uses of the assertive, exploratory energies that are so characteristic of human beings. They may also be mutually exclusive because if one occurs on a massive scale, the other probably will not”

–Frank White, *The Overview Effect*, 1981¹

Introduction

A theater of war can be defined as the entire land, sea, and air area that is involved in war operations.² A part of military strategy is to evaluate the theater of war for accessibility, affordability, and appropriateness for military operations. Outer space is a dangerous and unforgiving environment.

Beyond the Earth’s protective atmosphere, space cannot support human life. This environment is also demanding on materials used to construct spacecraft, which are exposed for extended periods of time to extreme temperatures and radiation. If outer space is to be considered as a theater of war, it needs to provide an advantage that surpasses the challenges of operating in such an environment. In addition, the benefit has to outweigh the cost of launching payloads into orbit and the possibility that assets can be destroyed on both sides.

¹White, Frank. *The overview effect: space exploration and human evolution*, third edition. AIAA.org. c2014. Accessed: <https://arc.aiaa.org/doi/book/10.2514/4.103223>

²Miriam-Webster Dictionary. Accessed from: <https://www.merriam-webster.com/dictionary/theater%20of%20war>

After decades of research, scientists now have an improved understanding of how a human body and spacecraft materials are affected by long-term exposure to the vacuum of outer space. However, up until now, no war has been waged in the space environment. Still, spacefaring nations are starkly aware of the dangers that could occur by crossing that line and bringing military operations into the space beyond.

The Outer Space Environment

The imaginary line defining outer space starts at 62 miles above the Earth's surface. It is defined as the airspace that exists beyond the Earth's atmosphere. This empty space has virtually no gas molecules, making it a near vacuum. Nevertheless, there are some types of particles in outer space that take up very little space, approximately five particles per cubic centimeter with decreasing density further from the Sun. They include dust, cosmic rays, and burning plasma propagated by solar winds, and they are affected by numerous factors, including magnetic fields.³

The outer space environment has no atmospheric pressure and excessive temperatures. On the sunlit side of an object at the Earth's distance from the Sun, high temperatures reach over 120 °C (248 °F), while the shaded side drops to −100 °C (−148 °F). Waves, such as radiation and light, flow freely through space.⁴

Outer space can be divided into regions: near-Earth, interplanetary, and interstellar. Interplanetary space (seen with telescopes) stretches to the edge of the Solar System, where it intersects with interstellar space and the heliosphere (see Fig. 3.1 depicting the layout of the Solar System). The heliosphere is like a bubble that wraps around our Solar System, forming a protective sphere. It is created by the magnetic particles in solar winds that interact with interstellar space. The boundary between interplanetary space and interstellar space is known as the heliopause and is thought to be roughly 110–160 astronomical units (AU) from the Sun. 1 AU is the mean distance between the Earth and the Sun, about 98 million miles.⁵

Earth's gravitational pull decreases as a spacecraft moves away from the center of Earth until microgravity or nearly zero gravity is reached. The prefix “micro” is added because the gravity measurement is close to but not exactly zero. Microgravity has a significant effect on human functions as well as materials and processes. Many of these effects have been discovered and documented through experimentation in outer space over the years.⁶

³Cessna, Abby. [Universetoday.com](https://www.universetoday.com/34074/interplanetary-space/). What is interplanetary space? 5 Jul 2009. [Internet].; [cited 2017 July 09]; Available from: <https://www.universetoday.com/34074/interplanetary-space/>

⁴NASA Quest. NASA. [Internet]. Quest.[nasa.gov](http://quest.nasa.gov). The outer space environment; Feb 28, 2013 [cited 2015 July 23]; Available from: <http://quest.nasa.gov/space/teachers/suited/3outer.html>

⁵Cessna, Abby. What is interplanetary space? 5 Jul 2009. [Internet]. [Universetoday.com](https://www.universetoday.com/34074/interplanetary-space/); [cited 2017 July 09]; Available from: <https://www.universetoday.com/34074/interplanetary-space/>

⁶NASA Quest. NASA. [Internet]. Quest.[nasa.gov](http://quest.nasa.gov). The outer space environment; Feb 28, 2013 [cited 2015 July 23]; Available from: <http://quest.nasa.gov/space/teachers/suited/3outer.html>

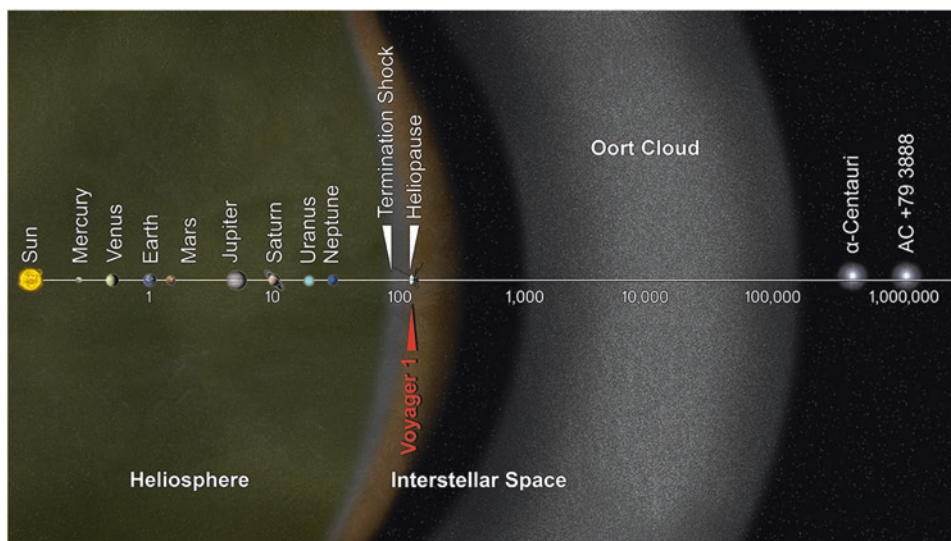


Fig. 3.1. The layout of the Solar System on a logarithmic scale. Image Credit: Artwork by NASA Goddard Space Center

Humans and spacecraft traveling in the extremes found in outer space need protection. Spacecraft need to be fabricated from materials that can tolerate the extreme temperatures and radiation. Because human life cannot naturally exist in outer space, artificial environments must necessarily provide life support that can function in such an environment.

This book focuses on unmanned spacecraft, satellites, weapons, missiles, and other technologies that could be components of a military conflict in outer space. Therefore, it is important to understand the long-term effects of outer space on the materials used to construct such items, including corrosion and radiation effects. This chapter focuses on the major issues affecting military operations in outer space, and how space as a military theater compares to a traditional war scenario.

The Costs and Challenges of Accessing Outer Space

Accessing and utilizing outer space is expensive. Firstly, Earth's gravitational effects must be overcome to successfully launch a payload. This requires a launch system, namely a rocket, capable of launching itself and its contents into Earth orbit. The spacecraft needs to achieve a speed of 17,500 mph in order to escape gravity.⁷ This requires a lot of fuel, which itself is heavy and expensive.

⁷Gannon, Megan. [Space.com](https://www.space.com/22470-reusable-rocket-launches-incredible-technology.html) Staff Writer. 23 Aug 2013. Incredible technology: how to make reusable rockets for cheap space travel. [Internet] [cited 2017 Jul 23]. Available from: <https://www.space.com/22470-reusable-rocket-launches-incredible-technology.html>

The cost of sending a payload such as a satellite into orbit around Earth depends on the type of launch system. The current cost for sending one pound into Earth orbit is \$10,000.⁸ Entrepreneur Elon Musk, the owner of SpaceX, aims to lower this cost to less than \$1000 per pound.⁹

In order for the spacecraft to be protected against the harsh environment of space, certain materials—expensive ones—must be used. The costs associated with manned space missions are astronomical compared to unmanned missions, as life support and redundant systems must meet the highest safety standards. These additional costs are not considered in this discussion of the military use of spacecraft in Earth orbit.

The Effects of the Outer Space Environment on Spacecraft

The outer space environment is extreme and harsh, characterized by an almost complete vacuum and the presence of a variety of particles, as discussed above. That is not to mention the presence of ultraviolet radiation, charged particle radiation, plasma, and temperature extremes. Add to those the ongoing threats of impact with unknown orbital debris, and spaceflight becomes quite challenging indeed.

Materials used to construct spacecraft are vulnerable to environmental dangers here on Earth that can degrade and contaminate system components. Such dangers vary based on the type of materials, their thicknesses, and the stress levels experienced.¹⁰ It is crucial to study the effects of long-term exposure to space on various materials in order to determine which ones are best suited for spacecraft construction. The space environment is difficult to simulate, so not surprisingly, materials are best studied in outer space. Such experiments that evaluate the durability of materials in space have been performed since the early 1970s, first using the Long Duration Exposure Facility (LDEF). The orbital facility was retrieved by the Space Shuttle and returned to Earth in 1990 after spending over 5 years in LEO. It tested the performance of spacecraft materials, components, and systems exposed to the environment of outer space for extended periods of time. The ISS is an ideal experimental platform to test long-term space environment effects. As a bonus, experiments can be sent back to Earth for post-flight analyses. Some of the effects studied and observed are summarized below.¹¹

⁸NASA [Internet]. [nasa.gov](https://www.nasa.gov/msfc/advanced-space-transportation-program/paving-the-highway-to-space) msfc. Advanced space transportation program: paving the highway to space; c2008 [cited 2017 July 23]; Available from: <https://www.nasa.gov/centers/marshall/news/background/facts/astp.html>

⁹Kramer, Sarah and Moser, Dave. 20 Jul 2016. Here's how much money it actually costs to launch stuff into space. [Internet] [cited 2017 Jul 25]. Available from: <https://www.businessinsider.com/spacex-rocket-cargo-price-by-weight-2016-6#does-this-sound-ridiculously-expensive-10>

¹⁰NASA. [Internet] [nasa.gov](https://www.nasa.gov). The International Space Station (ISS) Researcher's Guide. NP-2015-03-015-JSC.

¹¹NASA. [Internet] [nasa.gov](https://www.nasa.gov). The International Space Station (ISS) Researcher's Guide. NP-2015-03-015-JSC.

Near-Vacuum Effects

Exterior surfaces exposed to a near vacuum undergo the outgassing or the release of gas that was dissolved, trapped, or absorbed in a material. Outgassed molecules deposit on external surfaces, and more quickly on cold surfaces. The resulting molecular contamination can affect optical properties for spacecraft components as well as outer surfaces.

Atomic Oxygen Erosion

The low Earth orbit (LEO) environment, defined as 100–1240 miles above the Earth's surface, has a severe degrading effect on most non-metallic materials. Atomic oxygen (AO) is the single most significant component of material degradation in outer space at ISS altitude. AO is generated when short-wavelength UV radiation reacts with molecular oxygen in the upper atmosphere. It oxidizes many metals and reacts powerfully with materials containing carbon, nitrogen, sulfur, and hydrogen bonds, sparking reactions and erosion. Polymers containing fluorine, such as Teflon, experience increased reactivity to AO the longer they are exposed to UV radiation. Degradation can occur even with materials with AO protective coatings. Materials used on the surface of a spacecraft could erode, significantly reducing the spacecraft's orbit life. Other factors that can contribute to AO erosion of materials are the orbital parameters and orientation of the spacecraft to the sun and solar events. Visual evidence of AO erosion and the effect of UV radiation on spacecraft materials are shown in Fig. 3.2.¹²

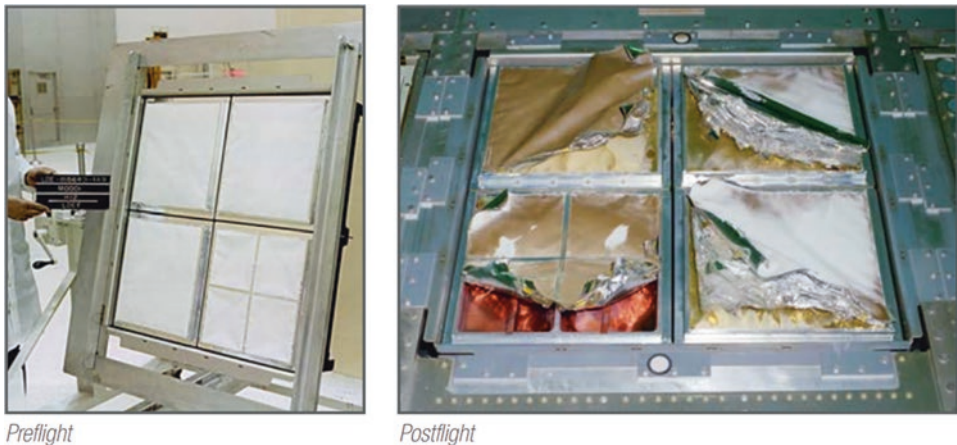


Fig. 3.2. Preflight and post-flight long duration exposure in a space experiment, showing atomic oxygen erosion and ultraviolet degradation. Image Credit: NASA

¹²NASA. [Internet] nasa.gov. The International Space Station (ISS) Researcher's Guide. NP-2015-03-015-JSC.

Radiation

Radiation is a form of energy that is produced as rays, electromagnetic waves, or particles (photons). This energy travels at a very high velocity, most often at the speed of light. Non-ionizing radiation includes innocuous waves such as visible light, heat, radio waves, microwaves, and radar. These happen all around us, passing through matter without breaking bonds or removing electrons from atoms. On the other end of the spectrum, ionizing radiation has sufficient energy to remove electrons from atoms, creating charged particles. Highly unstable atoms are created in this process. X-rays and cosmic rays are examples of ionizing radiation. Outer space radiation is the ionizing type, including particles shot into space during solar events, cosmic radiation (high energy sub-particles possibly originating from supernovae), and particles trapped in the Van Allen belts.¹³ Types of radiation in space are described in the NASA infographic shown in Fig. 3.3.

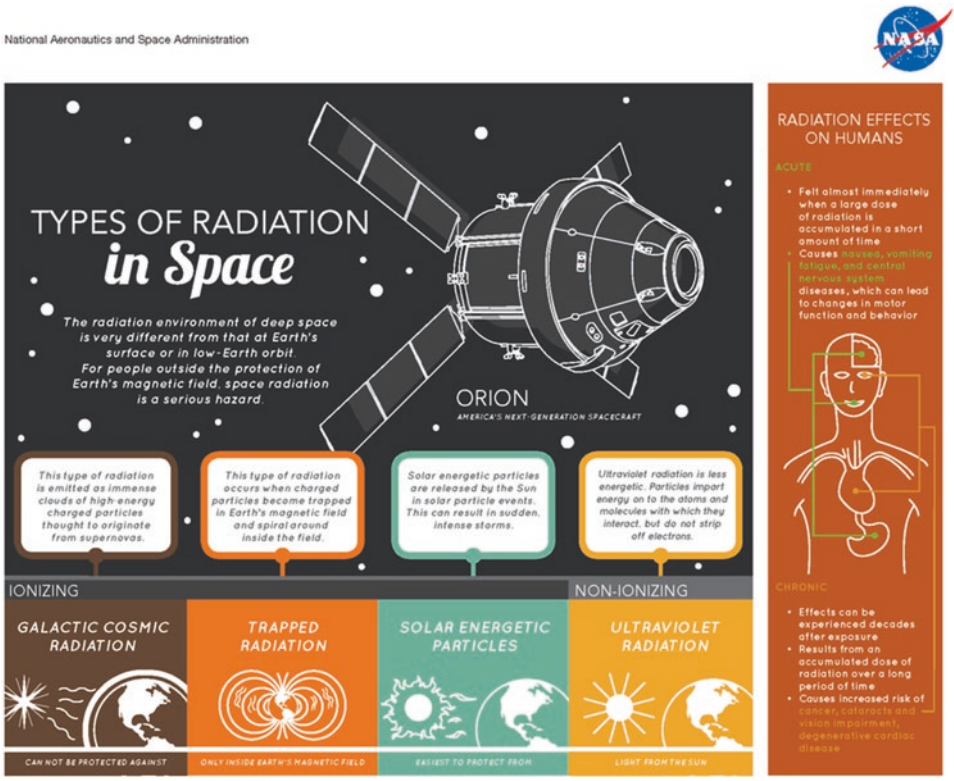


Fig. 3.3. Infographic on radiation in space. Image Credit: NASA

¹³Teodorescu, H. & Globus, A. 2005. Radiation passive shield analysis and design for space applications. SAE Technical Paper 114:179–188.

Ultraviolet light or solar photons is a type of electromagnetic radiation that originates from the Sun and is transmitted in waves or particles with a broad range of wavelengths known as the electromagnetic (EM) spectrum. The common designations of the spectrum include radio waves, microwaves, infrared (IR), visible light, ultraviolet (UV), X-rays, and gamma-rays. Exterior spacecraft materials on the exterior of the ISS are exposed to solar photon damage. UV generally darkens materials (see Fig. 3.4), while AO tends to bleach materials. UV radiation also damages polymers and in a near vacuum can lead to significant color changes. An illustration of AO erosion and radiation-induced effects on spacecraft materials is shown in the outer insulation of the Hubble spacecraft in Fig. 3.5.¹⁴

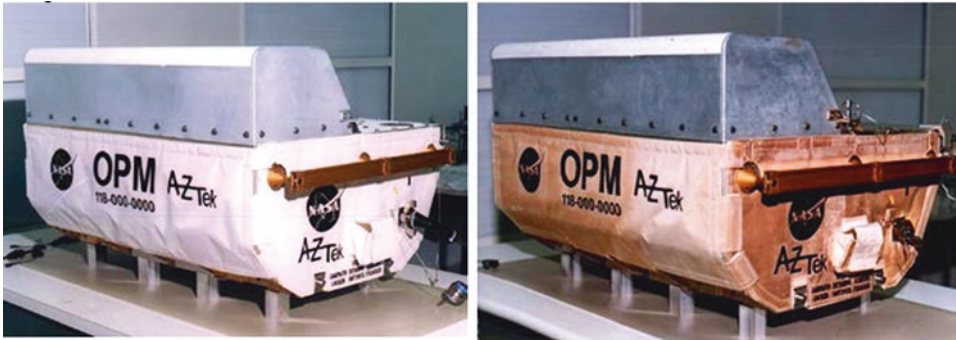


Fig. 3.4. Preflight and post-flight images of the Optical Properties Monitor, shown with insulation darkened by UV exposure after 9 months on the MIR Space Station. Image Credit: NASA



Fig. 3.5. Severe degradation to the outer layer of the Hubble Space Telescope's multi-layer insulation after 19 years of exposure. Image Credit: NASA

¹⁴NASA. [Internet] nasa.gov. The International Space Station (ISS) Researcher's Guide. www. NP-2015-03-015-JSC.

The Earth is protected from harmful radiation by a magnetic field that deflects the flow of hazardous forms of radiation away from Earth. Two large areas that surround the Earth, called the Van Allen belts, trap the charges inside them. The area surrounding the outside of Van Allen belts becomes saturated with high energy charged particles during a solar event. Events such as solar storms can be strong enough to produce the Aurora Borealis or affect electrical grids and damage satellites.¹⁵

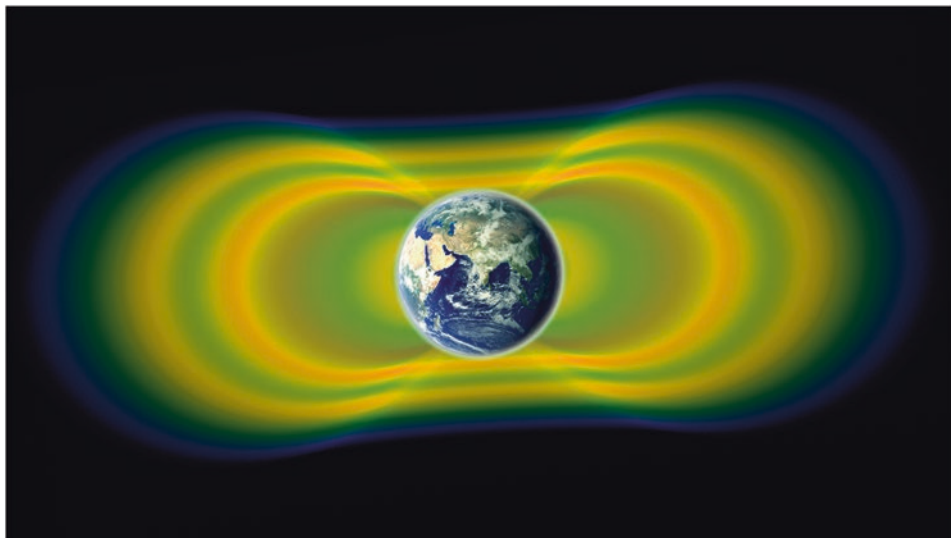


Fig. 3.6. The Van Allen belts surround Earth. The radiation is shown in yellow, with green representing the spaces between the belts¹⁶. Image Credit: *NASA/Goddard Space Flight Center*

Travel through the Van Allen belts into outer space is seen as problematic, due to the area's excessive concentration of charged particles. The altitudes of the belts vary—the center of the inner belt is approximately 1860 miles above the Earth's surface, and the center of the outer belt is approximately 9300–12,400 miles above the Earth, although some estimates lengthen it to 23,700 miles. Most LEO activities are well outside of this range, including the ISS, which is stationed about 240 miles above Earth, which exists below the lower altitude. Geosynchronous communications satellites orbit just inside the outer edge of this radiation belt at approximately 22,236 miles above Earth.¹⁷

¹⁵NASA. [Internet] nasa.gov. Van Allen probes. https://www.nasa.gov/mission_pages/rbsp/science/index.html

¹⁶NASA Science. Science News. [Internet]. [Science.nasa.gov](http://science.nasa.gov); c2014. Van Allen probes discover new radiation belt; Feb 28, 2013 [cited 2015 July 09]; Available from: http://science.nasa.gov/science-news/science-at-nasa/2013/28feb_thirdbelt/

¹⁷Editors of Encyclopedia Britannica Online. [Internet]. Britannica.com; c2014. Van Allen radiation belt; [cited 2015 July 09]; Available from: <http://www.britannica.com/science/Van-Allen-radiation-belt>

In outer space, the high energy particles are located everywhere and traveling so fast that it is difficult to stop them by shielding alone. Wave radiation must be battled by thick shielding. Thick materials are likely heavy and dense, making the materials problematic or too costly to transport or use to build spacecraft. New technologies or materials need to be developed to protect against the ionizing effect of space radiation. The military has extensive experience constructing radiation-hardened equipment used in case of bomb detonations. This knowledge can be translated into military spacecraft design.

In late 2014, NASA concluded a successful test flight of the Orion Multi-Purpose Crew Vehicle, measuring the effect of deep-space radiation on its radiation tolerant onboard electronics. Results indicate that Orion's highly complex avionics system performed without errors despite flying through extremely challenging radiation and thermal environments.¹⁸

Electronic components like microprocessors, solid-state memory, and network interfaces are sensitive to radiation. Most modern electronic components were not designed to operate in a radiation environment. LEO does not experience the same radiation levels that higher orbits or deep-space have. Applications in lower Earth orbits of relatively short durations (less than 5 years) that could tolerate the occasional data upset could utilize commercial off-the-shelf (COTS) electronics suppliers, particularly for cost-sensitive applications like small satellites. However, military and time-sensitive surveillance applications may require specialized equipment.¹⁹

Today's radiation-hardened space processors typically are single-processor systems based on existing commercial or military computers. They operate at maximum throughput, fault tolerance, and power levels. Air Force and NASA space experts anticipate that future missions will require wider variations of these factors. Electronic equipment is affected by ionizing radiation exposure by causing a build-up of static charge over time, which might release and cause damage or even failure to the equipment. Avionics can experience a range of problems, from complete burnout to the occasional single-event upset, bit errors, and data drops that can corrupt stored data and affect the reliability of the resulting transmissions.

There are several ways that electronic devices can be radiation hardened. One of the most common is to harden for "total dose radiation," or the amount of radiation the device is expected to withstand for its entire life before problems occur. Radiation effects can be reduced by using error-correction circuitry and triple redundancy, where two good results can outvote a corrupted one. Avionics can also

¹⁸Cole, Sally. [Internet] Military Embedded Systems. Orion spacecraft's avionics designed for reliability in deep space. 13 Mar 2015. [Mil-embedded.com](http://mil-embedded.com). [cited 2017 Sep 09]; Available from: <http://mil-embedded.com/articles/orion-avionics-designed-reliability-deep-space/>

¹⁹Military Aerospace Staff. Radiation-hardened space electronics enter the multi-core era. 21 Jun 2017. [Internet] [Militaryaerospace.com](http://www.militaryaerospace.com). [cited 2017 Nov 5]. Available from: <http://www.militaryaerospace.com/articles/print/volume-28/issue-6/technology-focus/radiation-hardened-space-electronics-enter-the-multi-core-era.html>

be radiation-hardened by placing shielding around the electronics, but it is expensive and the shielding packaging is heavy, which adversely affects launch costs. Demand for rad-hard electronic parts is relatively low, which can drive up their costs even more. Possible solutions include redundant subsystems, selective shielding, and selective COTS electronics for increased reliability. Figure 3.7 illustrates the NASA Orion spacecraft, which went on a test flight in 2015 as a step to NASA's journey to Mars and demonstrates the use of rad-hardened equipment.²⁰



Fig. 3.7. The avionics and electronics used in the NASA Orion spacecraft are ruggedized and radiation hardened to endure extreme radiation and temperatures. Image Credit: NASA

Redundant multicore processors are being developed by computer engineers at the Curtiss-Wright Corporation to not only block radiation-induced single-event effects but also recover quickly without disruption when upsets occur. Curtiss-Wright is delivering rugged, space-qualified data acquisition and network technologies to both the Orion spacecraft and the SLS launch vehicle. The Orion EM-1 flight will use the Curtiss-Wright-developed MnACQ-2000 Miniature Network Data

²⁰ Military Aerospace Staff. Radiation-hardened space electronics enter the multi-core era. 21 Jun 2017. [Internet] [Militaryaerospace.com](http://www.militaryaerospace.com/articles/print/volume-28/issue-6/technology-focus/radiation-hardened-space-electronics-enter-the-multi-core-era.html). [cited 2017 Nov 5]. Available from: <http://www.militaryaerospace.com/articles/print/volume-28/issue-6/technology-focus/radiation-hardened-space-electronics-enter-the-multi-core-era.html>

Acquisition System (shown in Fig. 3.8), a compact, stackable unit that analyzes and transmits instrumentation data to designated network nodes. Each of the COTS-based units built for Orion EM-1 include a radiation tolerant power supply.²¹

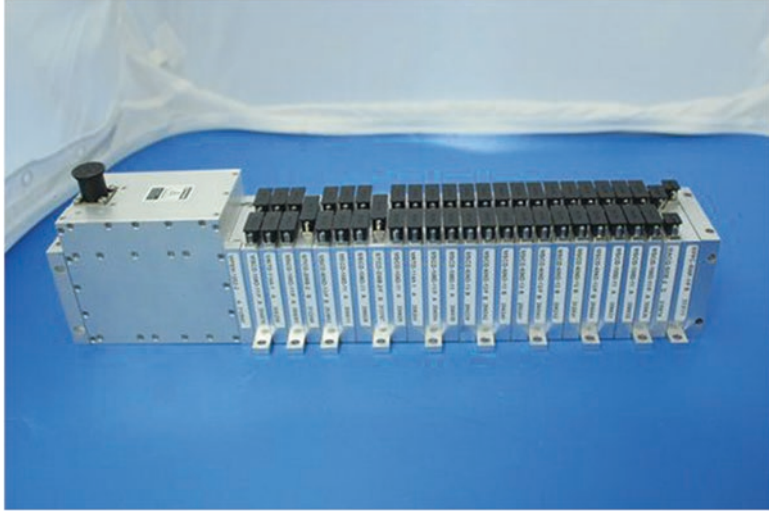


Fig. 3.8. Curtiss-Wright is delivering its MnACQ-2000 Miniature Network Data Acquisition System for the NASA Orion spacecraft and the Space Launch System (SLS). These data-acquisition systems are hardened against the effects of space radiation. Image Credit: NASA

Another approach to the development of hardened electronic components works from the ground up. Referred to as “rad-hard by design,” it can be an expensive and a time-consuming process. Yet, it sometimes is the only solution for electronic components that are crucial for protecting human lives or ensuring the success of important orbital and deep-space missions.

Advancements in electronic components, specifically the decreased size of modern chips, help lessen their exposure to total-dose radiation. One of today’s rad-hard design projects is the High Performance Spaceflight Computing (HPSC) Processor Chiplet program. US government space experts (NASA and the US Air Force Research Laboratory at Kirtland Air Force Base, NM) are working with the Boeing Company to create a new generation of radiation-hardened microprocessors for a wide variety of space applications. The nearly \$26 million contract was

²¹ Wranovics, John. Curtiss-Wright ships miniature network space data acquisition system for NASA’s Orion spacecraft program. 3 Apr 2017. [Internet] [curtisswrightds.com](https://www.curtisswrightds.com). [cited 2017 Nov 10]. Available from: <https://www.curtisswrightds.com/news/press-release/cw-ships-miniature-network-space-data-acquisition-system-for-orion-spacecraft-program.html>

awarded in early 2017 by the NASA Goddard Space Flight Center. Applications for the HPSC processor will include military surveillance and weapons systems, human-rated spacecraft, habitats and vehicles, and robotic science and exploration platforms. System applications range from small satellites to large and complex civilian and military equipment and missions. NASA is also looking to Boeing to develop technologies that can manage its own electricity demands to preserve power resources, especially on deep-space missions far from Earth. The HPSC program concludes in late 2020 or early 2021, after which the technology will be ready for deployment.

Aside from the HPSC program, NASA experts are considering additional plans for radiation-hardened computer components, such as general-purpose graphics processing units (GPGPUs), field-programmable gate arrays (FPGAs), and volatile and non-volatile memory. The problem, as always, is funding.²²

Plasma

The universe is 99.9% plasma, defined as the fourth state of matter (solid, liquid, gas, plasma). Plasma behaves like an extremely hot gas—its atoms split up into electrons and ions capable of moving independently of each other. These electrically charged particles enable it to conduct electricity and be affected by magnetic fields. The plasma environment varies with solar activity and altitude from the Earth's surface. Electrons can affect any spacecraft surface, while ions can only impact surfaces on the leading edge. This process can lead to a negative charge buildup, which increases the possibility of high-voltage solar arrays disruption. The negative charge can also affect the conductive coatings intended to bleed off static charge on a spacecraft.²³

Temperature Extremes

Spacecraft move in and out of sunlight while orbiting Earth. The spacecraft material's thermal properties determine the degree to which their material experiences temperature extremes. The cyclic temperature variations are generally -120°C to $+120^{\circ}\text{C}$, but other factors can contribute to greater temperature swings. A cooling system is required to keep temperatures from rising above the maximum operating temperature. A suitable construction material (aluminum) can distributed heat

²² Military Aerospace Staff. Radiation-hardened space electronics enter the multi-core era. 21 Jun 2017. [Internet] [Militaryaerospace.com](http://www.militaryaerospace.com). [cited 2017 Nov 5]. Available from: <http://www.militaryaerospace.com/articles/print/volume-28/issue-6/technology-focus/radiation-hardened-space-electronics-enter-the-multi-core-era.html>

²³ NASA. [Internet] nasa.gov. Plasma, plasma, everywhere. https://science.nasa.gov/science-news/science-at-nasa/1999/ast07sep99_1

along the structure of the satellite. Paint on the spacecraft surface with suitable coating material as well as insulation blankets can also be used. These techniques are all part of a passive thermal control system.

Satellites in any orbit require a surface coating to manage the thermal loads in that orbit. Thermal radiators manage internal heat generated by electronics. There are a few options for the management of thermal control, many of which prohibitively impact the satellite's budget. Partially active or passive components that are low cost and reliable can be used to achieve reasonable temperature control.

Reflections

Very little was known about the harmful effects of the outer space environment on both spacecraft and humans during the early space missions of the United States and the USSR. Once it was established that humans could survive spaceflight and explore and work in space, attention shifted to problems that could result from long-term exposure. In addition to environmental issues, we know that orbital debris and asteroid fragments in outer space can destroy spacecraft while creating more debris. Removing this orbital debris and making future spacecraft safe from such collisions remain a challenge. Finally, spacecraft materials need to be designed to withstand extreme temperature changes and different types of high radiation.

The hazards of orbital spaceflight provide trials that must be met with future scientific and technological achievements. The pace of embedded computing technology development is placing pressure on satellite and spacecraft designers, who must deliver reliable systems at low costs.

4

Space Debris as a Weapon

“Tackling the problem of space debris is one of humankind’s greatest environmental challenges, but it is also perhaps the one that is the least known.”

–Dr. Hugh G. Lewis¹

Introduction

We often look up to the night sky to see shooting stars, the International Space Station, and satellites streaking across the sky. There are thousands of objects orbiting Earth, and within minutes under a dark sky, both satellites and space debris can be seen with the naked eye. You can also use a sky tracker app on your cellphone held up to the night sky to see spacecraft and space debris moving across the sky. Space debris includes operating manmade spacecraft and satellites, space junk (defunct spacecraft or individual objects caused by a collision or explosion), as well as natural objects like meteoroids that orbit about the Sun.

Satellites and rockets, launched into space by the hundreds for decades, are left as space garbage when they become inoperative. Space junk is made up of dead satellites as well as discarded upper-stage rockets, once used to boost satellites into orbit, and even articles that have been set loose by astronauts by mistake. Examples include Ed White’s glove, which he dropped in 1965 on his first American spacewalk. Another example is the tool kit that slid from NASA astronaut Heide Stefanyshyn-Piper’s hand when she was repairing a solar panel on the

¹Radowitz, John. [Internet] Mirror.co.uk. 19 Nov 2016. [cited 2018 Jul 16]; Available from: <https://www.mirror.co.uk/science/space-junk-one-humankinds-greatest-9289084>

International Space Station during a spacewalk in 2008.² It is estimated that there are as many as three quarter of a million pieces of debris that are orbiting the Earth right now.³ They travel at very high velocities—a minimum of 17,500 mph, the minimum speed needed to maintain a stable orbit. Even a small chunk of debris is travelling fast enough to damage or even destroy a spacecraft or satellite that it happens to be in its path.⁴

There are potential collisions in orbit every day—cases where debris passes closely to a satellite or spacecraft. Risks of impending collisions between satellites or spacecraft have been reported but not to the extent often depicted in popular culture, such as in the film *Gravity*. Still, we can predict how space debris could create just as much havoc as intentional high-speed weapons.

Spacecraft (even those that are inoperative) are capable of remaining in Earth orbit for a long time until atmospheric drag eventually pulls the spacecraft back to Earth, a process that could take years or even decades. Up until then, the object remains a piece of space junk unless there is an onboard capability to conduct a deorbit burn. A majority of all debris is located in low Earth orbit (LEO), which is the most common region for manned spacecraft and satellites (about 99–1200 miles above the surface of the Earth).⁵ Objects below that altitude region will quickly be pulled back toward Earth as the orbit decays due to gravity and Earth's atmosphere. This chapter explores the challenges of how to handle space debris to make orbiting in space safe.

The Dynamics of Orbital Debris Collisions

A spacecraft launched from the surface of the Earth needs to accelerate to at least 25,000 mph (7 miles per sec) to completely escape Earth's gravity. This requires a huge amount of energy. A satellite does not have to achieve full escape velocity to be launched into a stable Earth orbit—it must attain the orbital velocity required to balance Earth's gravitational pull on the satellite with the satellite's tendency to keep going, or its inertia. Gravity pulls the spacecraft back toward Earth's center, just enough to keep the satellite on a curved path around the Earth's surface. In order to achieve a stable low Earth orbit at an altitude of 150 miles, a spacecraft

² Clark, Stuart. 2010. Who you gonna call? Junk busters!. *New Scientist*, 2017(2777), 46–49.

³ Science Editor. [Internet] [telegraph.co.uk](https://www.telegraph.co.uk/science/2017/04/21/750000-pieces-debris-orbiting-earth-threaten-future-spaceflight/). 740,000 pieces of debris orbiting Earth threaten future of spacecraft, warn experts. 21 Apr 2017. [cited 2018 Jul 16]; Available from: <https://www.telegraph.co.uk/science/2017/04/21/750000-pieces-debris-orbiting-earth-threaten-future-spaceflight/>

⁴ Zenko, Macah. FP. [Internet]. [Foreignpolicy.com](http://foreignpolicy.com/2014/04/21/waste-of-space/); c2014. 135 million pieces of junk are orbiting Earth at 18,000 mph—and US space dominance is in danger of being ripped to shreds.; 21 Apr 2014 [cited 2017 Oct 12]; Available from: <http://foreignpolicy.com/2014/04/21/waste-of-space/>

⁵ Zenko, Macah. FP. [Internet]. [Foreignpolicy.com](http://foreignpolicy.com/2014/04/21/waste-of-space/); c2014. 135 million pieces of junk are orbiting Earth at 18,000 mph—and US space dominance is in danger of being ripped to shreds.; 21 Apr 2014 [cited 2017 Oct 12]; Available from: <http://foreignpolicy.com/2014/04/21/waste-of-space/>

has to accelerate to 17,000 mph.⁶ An object in a 150-mile orbit is still experiencing Earth’s gravity, and eventually its orbit will decay unless small onboard jets increase its velocity. Left uncorrected, the satellite’s velocity will decrease and the object will eventually fall back to Earth.

If there are multiple bodies in a 150-mile orbit above the Earth, they should be stable and remain a safe distance from other objects. However, objects that are launched and pass through other orbits to achieve a higher orbit can potentially cross paths and come close to colliding with objects along the way. There is no Federal Aviation Administration (FAA) of space activities, although there are some monitoring activities for the International Space Station and other high-risk spacecraft. These are described later in this chapter.

Collision avoidance is a possibility for some spacecraft, but not all craft are equipped to move on demand to avoid another object traveling thousands of miles per hour. The probability of collision increases as the number of spacecraft in orbit and traveling through orbits increases. The launching of small spacecraft has greatly increased over the past several years and shows no sign of diminishing. Figure 4.1 illustrates the number of launches by country over the past six decades. Since 1957, an average of 143 spacecraft has been launched per year. In all, 8593 spacecraft (satellites, human spaceships, and planetary probes) had been launched by late-2017. The Space Race is largely responsible for the launches by the US and the USSR in the 1960s up through early 1970s. Private industry and other

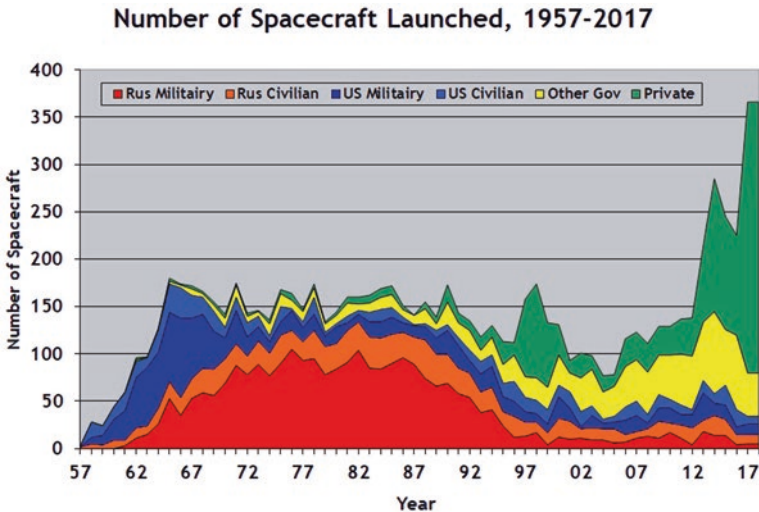


Fig. 4.1. Number of spacecraft launched (1957–2017). Image Credit: *Claude Lafleur, cooptel.qc.ca*

⁶NASA, [Internet]. [nasa.gov](https://www.nasa.gov); c2001. What is an orbit?; Sep 10, 2003 [cited 2017 Oct 19]; Available from: https://www.nasa.gov/audience/forstudents/5-8/features/orbit_feature_5-8.html

governments contribute to the growth that first started in the 1990s, with the highest peaks occurring over the past 5 years.⁷

Collisions seem inevitable due to the large numbers of objects travelling in low Earth orbits. Even small pieces of debris, because of their high speeds, can collide with other objects and cause explosions. The hundreds or thousands of particles resulting from the collision will be traveling at the same speed as any object in that orbit. Such particles have an orbital time of 90 min, meaning it would take an hour and a half for them to complete one revolution around Earth. In the movie *Gravity*, the fragmented objects resulting from a major collision reappear 90 min later, colliding with other objects in their way.

The associated kinetic energy from orbital debris is dependent on its mass and the square of its velocity ($\text{Kinetic Energy} = \frac{1}{2} \text{Mass} \times \text{Velocity}^2$). The velocity is approximately 4.8 mi/s in a typical LEO (124 miles), with impact velocities usually higher (6 mi/s) due to colliding debris at different orbital inclinations. A small 1-mm object does very little damage, but if that object increases to 3 mm, it produces energy similar to that of a bullet. As the debris size and mass increases, so does the kinetic energy. For objects that are 5 cm in size, the resulting collision is similar to being hit by a bus. At 10 cm, the force would be equivalent to a large bomb. Smaller debris fragments from 1 mm to 1 cm in size will most likely not penetrate a spacecraft, but those closer to 1 cm have a higher chance of piercing a critical component. As debris approaches 10 cm in size, any impact will create even more small debris that will become a danger to other spacecraft.⁸

Debris caused by a satellite collision can spark a chain reaction with other objects found in their path. Each piece of collision debris in orbit keeps moving at a high orbital speed until it hits something, or eventually, over a long period of time, burns up in the Earth's atmosphere when gravity forces its return. In 1978, NASA scientist Donald Kessler proposed a theory called the Kessler syndrome, which describes the continuing process of impacts in the congested LEO. Starting with one explosion, hundreds or thousands of fragments are generated. Each individual piece of debris is capable of colliding with other spacecraft, creating hundreds or thousands more pieces orbiting at high speeds in the path of other objects. Soon, the entire LEO would be littered, preventing any launched satellite to pass through to higher altitudes unscathed. Kessler says it best in a 2012 Space Safety article: "The cascade process can be more accurately thought of as continuous and as already started, where each collision or explosion in orbit slowly results in an increase in the frequency of future collisions." Kessler stated that the best way to

⁷Lafleur, Claude. [Internet]. Spacecraft Encyclopedia, c2017. [cited 2017 Oct 24]; Available from: <http://claudelafleur.qc.ca/Spacecrafts-index.html>

⁸The Aerospace Corporation. [Internet]. aerospace.org; c2017. Space debris basics. [cited 2017 Oct 24]; Available from: <http://www.aerospace.org/cords/all-about-debris-and-reentry/space-debris-basics/>

avert the exponential growth of collisions was to decrease the number of non-operating spacecraft and other objects in orbit.⁹

After decades of launching spacecraft into orbit, there have been very few efforts to de-orbit non-functioning spacecraft or orbiting fragments. One of the biggest concerns by scientists is that the situation will be out of control unless a concerted effort is made by countries with orbiting spacecraft to address the issue. The problem is technologically complex and very expensive, and international coordination is tricky. One question is who would lead the effort and how payment for removal services would be arranged.

Figure 4.2 shows a graph of the numbers of debris objects by altitude above Earth (January 2013). The major peak occurs from approximately 310–621 mi, which corresponds to the orbital altitude of the majority of satellites. Two spikes occur in the peak. They are associated with two collisions that generated a large number of debris fragments. The first event was identified as the hundreds of thousands of fragments created by the collision between two communication satellites on February 10, 2009—the Iridium 33 (US) satellite and a defunct Soviet Union-era satellite (Cosmos 2251). Most of these debris fragments will eventually decay

The collision of the Iridium 33 and Cosmos 2251 satellites significantly altered the amount and distribution of orbital debris in LEO.

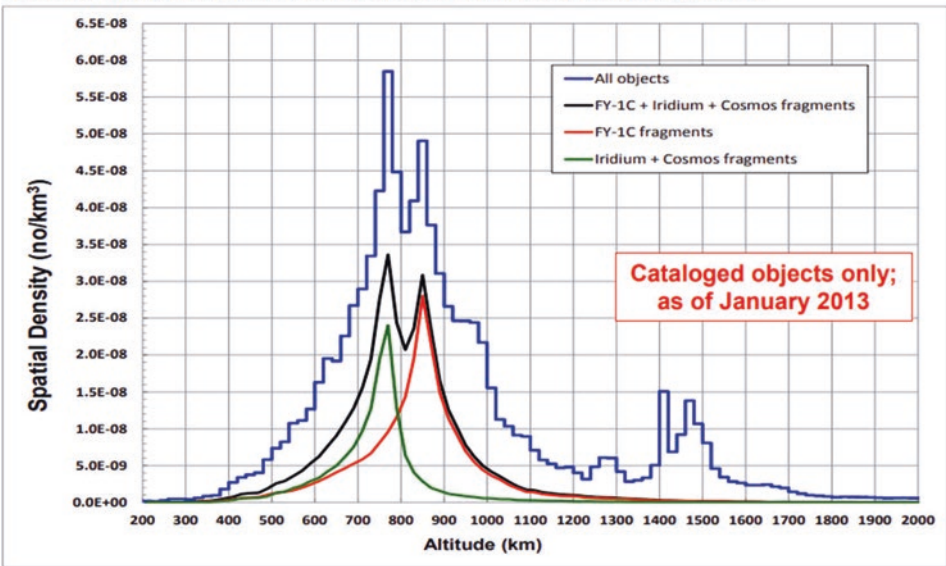


Fig. 4.2. Space debris density by altitude above Earth (2013). Image Credit: NASA

⁹Space Safety Magazine. [Internet]. aerospace.org; c2014. The Kessler Syndrome. [cited 2018 Jul 18]; Available from: <http://www.spacesafetymagazine.com/space-debris/kessler-syndrome/>

and fall back to Earth, but until then, they will remain a potential danger to other spacecraft for decades.¹⁰

The second event was determined to be the outcome of the destruction of a non-operational Chinese meteorological satellite Fengyun-1C on January 11, 2007. It was deliberately demolished by a ballistic missile kinetic kill vehicle (KKV) launched from the China's Xichang Space Launch Center. The KKV was not launched into orbit but travelled instead through space at over 20,000 mph following a ballistic arc. The resulting collision generated thousands of debris fragments, most of which will keep orbiting Earth for decades. The resulting ring of debris travels in an orbit similar to the original destroyed satellite. This particular collision created the largest cloud of debris fragments ever generated by a single event in orbit.¹¹

Geosynchronous satellites that are positioned roughly 26,000 miles above the equator have the same rotation period as the Earth, allowing them to remain in approximately the same location above Earth for long periods of time without expending a lot of fuel. This is commonly used for telecommunications signals and other applications. Satellites in geostationary orbit cannot be easily brought down to Earth's atmosphere. Instead, the remainder of a satellite's fuel is used to place it into a so-called "graveyard orbit." However, with little oversight, it is a common practice to leave the satellites stranded (Fig. 4.3).

The growing number of orbiting space objects, including debris, is illustrated in Fig. 4.4. The increased number of objects over the years has an impact on all spacecraft, including the ISS as well as private and government satellites that provide vital communication and surveillance services. As the probability of collisions increases, true disruption of these services for days or weeks becomes a real possibility. In addition, damages to US satellites are impossible to repair now that the Space Shuttle orbiter is not available to rendezvous and fix the craft. The preference would be to evade the threat if possible or take defensive measures beforehand in order to safeguard the spacecraft. Advanced warning provides the time to analyse data and determine a course of action to save a spacecraft or a life. However, not all spacecraft are equipped with such capabilities. Recently, in July 2018, the European Space Agency was able to change one of its satellite's orbit in order to avoid a possible collision with a piece of space junk about 400 ft away. CryoSat 2 studies glaciers sea levels and was faced with a slight probability of

¹⁰David, Leonard. [Internet]. Space.com; c2014. Effects of worst satellite breakups in history still felt today; June 28, 2013 [cited 2016 Feb 15]; Available from: <http://www.space.com/19450-space-junk-worst-events-anniversaries.html>

¹¹Johnson, Nicholas et al. [Internet]. NASA.gov archives. The characteristics and consequences of the break-up of the Fengyun-1C spacecraft. 2007. IAC-07-A6.3.01 [cited 2017 Oct 12]; Available from: <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070007324.pdf>

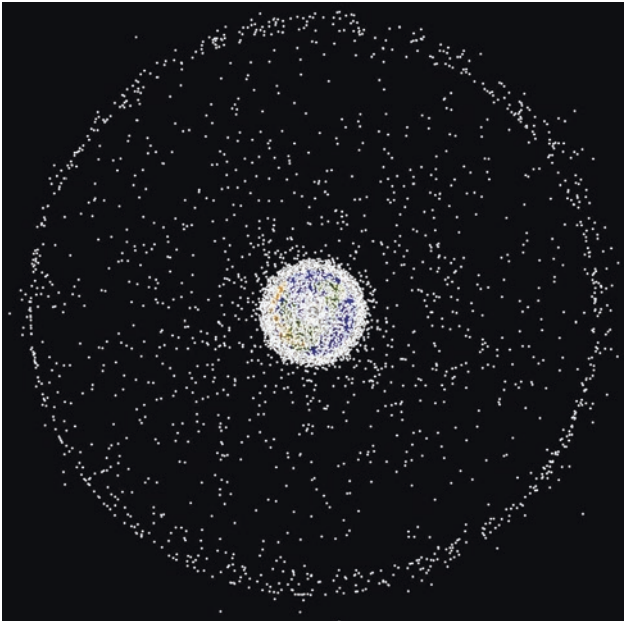


Fig. 4.3. Space debris surrounding Earth. A polar image showing concentrations in low Earth and geosynchronous orbits. Image Credit: NASA

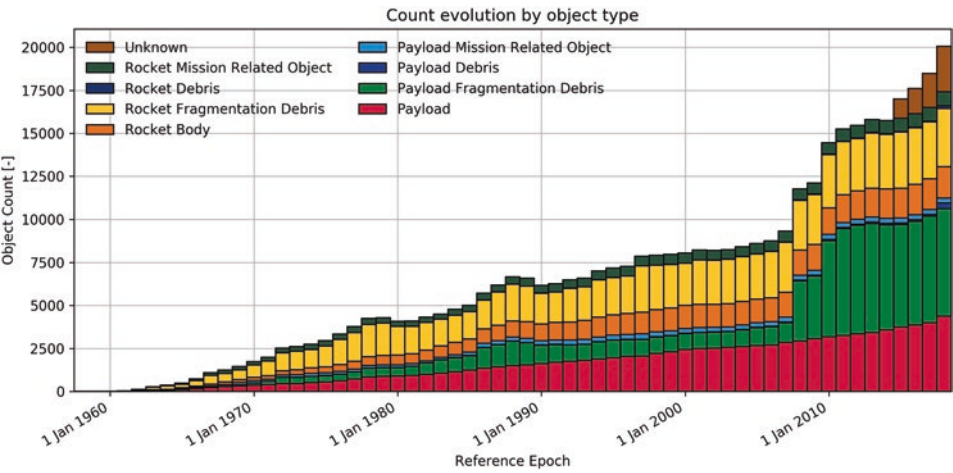


Fig. 4.4. Growth of orbital space objects and debris over time. Image Credit: NASA

hitting the object.¹² In a directive signed in June 2018, President Donald Trump ordered his administration to prioritize the hazards of space debris and space traffic control in order to put the US back in a leadership role in outer space.

As previously explained, even minor collisions can wreak enormous havoc, because spacecraft, space junk, and satellites are flying around Earth at extremely high velocities. Large pieces of space debris can be broken into smaller pieces that are more difficult to track but are still capable of impacting active satellites. International issues can arise when spacecraft from one country collide with another either by accident or deliberately, such as China's 2007 missile test that demolished an old satellite. To help prevent collisions, it would make sense to monitor airspace in the same manner as the FAA does for airplanes. However, this is an extremely complex undertaking. The US Air Force Space Surveillance System, a radar system known as the "Space Fence," was operational from 1961 to 2013, when it was taken down for a technical upgrade. The system was capable of detecting space objects and debris at an altitude of approximately 19,000 mi. Objects were identified, catalogued, and utilized if needed for collision avoidance. The US space catalogue is maintained at the Joint Space Operations Center (JSpOC) at Vandenberg Air Force Base. Data is collected and analyzed from other sources to generate an integrated view of Earth-orbiting spacecraft. While the Space Fence is offline, there has been concern about the lack of ability to track objects. Stopgap measures include radar surveillance systems, which have been performing satisfactorily in the interim.¹³

The new Space Fence, consisting of a powerful electronically steered radar system, is nearing completion, with a goal of becoming operational in 2019 (see Fig. 4.5). In 2014, the US Air Force awarded the Lockheed Martin Corporation a nearly billion-dollar contract to adapt optical and laser tracking technology first tested in the war zones of Iraq and Afghanistan. Located on the Kwajalein atoll in the Pacific, the new system will be able to track as many as 200,000 pieces of orbiting debris travelling in LEO. "Previously, the Air Force could only track and identify items the size of a basketball," said Dana Whalley, the government's program manager. "With the new system, we'll be able to identify items down to the size of a softball. This will significantly increase our capability."¹⁴

¹² Bartels, Meghan. [Internet] [Space.com](https://www.space.com/41126-european-satellite-dodges-junk-in-orbit.html). Europe's ice-watching satellite dodges space junk in orbit. 10 Jul 2018. [cited 2018 Jul 12]; Available from: <https://www.space.com/41126-european-satellite-dodges-junk-in-orbit.html>

¹³ Defense Industry Daily Staff. Don't touch their junk: USAF's SSA tracking space debris. Defense Industry Daily. 26 Aug 2014.

¹⁴ Hennigan WJ. Watching over a cosmic minefield; Lockheed's 'space fence' surveillance system will track debris orbiting earth. Los Angeles Times. 05 Jul 2014.

The new Space Fence will be the first stage in the process of feeding data to the Joint Space Operations Center at California's Vandenberg Air Force Base. When the radar detects an object orbiting Earth, it will report the object and calculate its trajectory, either updating an existing record or creating a new one in the catalogue. The Space Fence will locate an object in orbit, project its future path, and predict any future potential collisions. In addition, it will extend its ability to track objects to a more distant geostationary orbit, with an expanded focus on LEO.¹⁵

The size of satellites is shrinking similar to all electronics. The ability of the Space Fence to track small objects comes at an appropriate time as the small satellite market only grows. In addition to tracking peaceful satellites, it is also of military importance, able to identify and track anti-satellite weapons, some of which are satellites launched to interrupt or disable space-based communications and reconnaissance hardware. This is not a new threat. Russia has experience creating spacecraft capable of maneuvering next to a target and spying on it, disabling it, or grabbing onto it. The new Space Fence will be a valuable component in monitoring any attempts at militarization in orbit.¹⁶

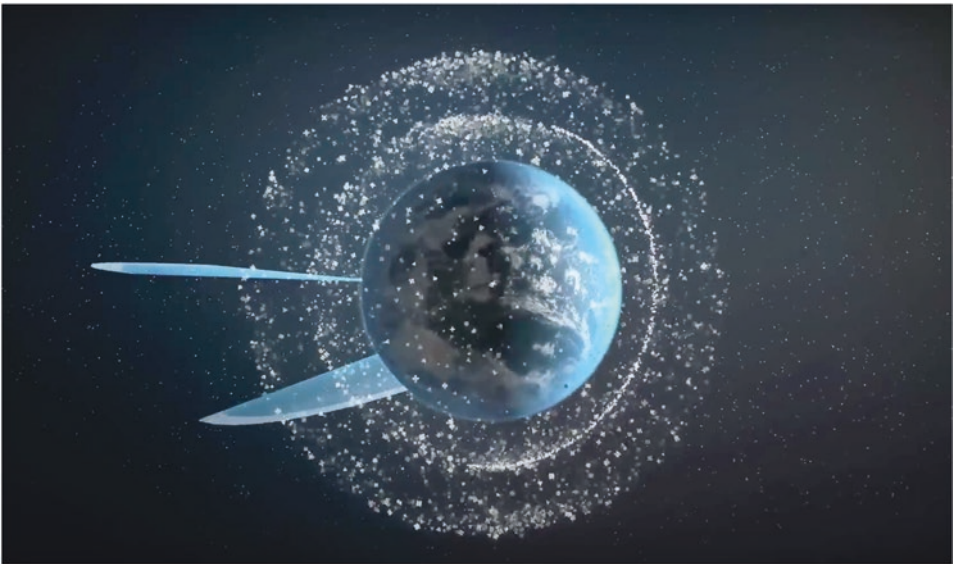


Fig. 4.5. The new Space Fence, to be completed in 2019, will spot space junk, small satellites, and orbital weapons. Image Credit: *Popular Mechanics*

¹⁵ Pappalardo, J. [Internet]. [Space.com](https://www.space.com); New 'Space Fence' will spot space junk, small sats and orbital weapons. 16 Apr 2018. [cited 2018 Jul 19]; Available from: <https://www.popularmechanics.com/space/satellites/a19831013/space-fence-update/>

¹⁶ Mola, Roger. Air & Space Magazine. [Internet]. [Airspacemag.com](https://www.airspacemag.com); How things work: Space Fence. Feb 2016. [cited 2018 Jul 19]; Available from <https://www.airspacemag.com/space/how-things-work-space-fence-180957776/>

The new Space Fence program will function in the shorter wavelength S-band frequency range, replacing VHF used in the old system. The architecture will be updated as well, bringing the detection capabilities and analysis to a more advanced level. Tens of thousands of additional space objects previously not tracked will be identified with this wider-band capability. In addition, it will be able to scan a wider region by employing better locations around the world for the network sensors.¹⁷

At the current resolution, researchers have categorized more than 20,000 orbiting items about the size of a basketball. However, it has been estimated that there are thousands of fragments of debris even smaller than the size of a baseball that could still impair a functioning spacecraft because of their significant velocities. “The greatest risk to space missions comes from non-trackable debris,” said Nicholas Johnson, NASA chief scientist for orbital debris.¹⁸

At least nine collisions between non-classified satellites have been identified in the past 50 years, and the risks are mounting every year. Space debris proximity alerts have occurred regularly on the ISS. The spacecraft can move out of the way in order to avoid a collision, although it can take more than a day’s time to plan and carry out an evasive maneuver. If a threat was looming, the crew would have to go inside smaller escape vehicles.¹⁹

The use of a laser cannon has been proposed as a method to slow objects down or to destroy space garbage. The Russian space agency Roscosmos recently submitted a proposal to the Russian Academy of Sciences to convert a 10-ft optical telescope into a space garbage destroyer. It will fire at space junk, vaporizing it using laser ablation, the process that removes layers on the surface of a metal, breaking down chemical bonds. Japan and China have both proposed similar concepts.²⁰

Other proposed approaches include a spacecraft launched as a sort of garbage truck, collecting smaller chunks of debris and non-functional satellites. The Space Shuttle orbiter might have filled this type of roll, but since the program has been cancelled, there are no similar US vehicles that could be used for this application. Russia has proposed a nuclear-powered spacecraft for long-duration missions to perform the duties of picking up or destroying debris objects. The idea is promising, but there is resistance to nuclear propulsion systems and the dangers they pose. The concept shows potential, as they would be able to maneuver to other

¹⁷Defense Industry Daily Staff. Don’t touch their junk: USAF’s SSA tracking space debris. Defense Industry Daily. 26 Aug 2014.

¹⁸Truong K. Wayward space junk prompts astronauts to shelter in cosmic lifeboat. The Christian Science Monitor. 16 Jul 2015.

¹⁹Truong K. Wayward space junk prompts astronauts to shelter in cosmic lifeboat. The Christian Science Monitor. 16 Jul 2015.

²⁰Staff. [Internet]. Syfy.com; Russia’s sci-fi laser cannon is going to obliterate space junk. 19 Jun 2018. [cited 2018 Jul 19]; Available from <http://www.syfy.com/syfywire/russias-sci-fi-laser-cannon-is-going-to-obliterate-space-junk>

orbits and perform a variety of tasks, pulling rocket stages or satellites to lower orbits and clearing debris.²¹

The latest idea from Japan's Aerospace Agency (JAXA) is to use a magnetic net to draw closer and catch metal debris. The agency has teamed up with a fishing equipment company to create a unique net that could be used to catch some of the orbiting space junk. The electrified net, made of ultra-thin stainless steel and aluminium, would first capture and then slow down the debris so that it burns up in Earth's atmosphere.²²

Each of these methods has positive and negative aspects. It is at least reassuring that there is a significant amount of research being done on space junk removal methods. An equally important endeavour is seeking to limit the quantity of orbiting debris, holding each company or country of origin responsible for its own spacecraft in orbit. There is the issue of enforcement and who would take on that responsibility. The guidelines as outlined in the Space Treaty of 1967 state, "States shall be responsible for their national activities in outer space, whether carried on by governmental or non-governmental entities." In addition, the treaty says, "States shall avoid the harmful contamination of outer space."²³ This has been followed to a limited extent. Currently, removing space debris would require space-faring countries with spacecraft in orbit to agree on the procedures, and it is doubtful whether countries are willing to collaborate on this effort and to what extent. Several countries have shown concern over space debris issues. China has recently established an agency to track and deal with space debris in order to protect its own assets.²⁴

After the Iridium-Russian satellite collision in 2008, United Nation member countries adopted a resolution to establish space debris guidelines, calling for the removal of non-operational spacecraft from low Earth orbit.²⁵ "The prompt implementation of appropriate space debris mitigation measures is in humanity's common interest, particularly if we are to preserve the outer space environment for future generations," said, Mazlan Othman, Director of the UN Office for Outer Space Affairs (UNOOSA).²⁶ The first step in the resolution puts forth

²¹ Anonymous. 'Space towboats' to have nuclear engines. Interfax: Russia & CIS general news-wire [Moscow]. 11 Feb 2010.

²² McCurry J. In space, no one can hear you clean: The Guardian. 2014 Feb 28;Sect. 25.

²³ Zenko, Micah. [Internet]. Foreignpolicy.com; c2015. Waste of space.; April 21, 2014 [cited 2015 Aug 08]; Available from: <http://foreignpolicy.com/2014/04/21/waste-of-space/>

²⁴ Zhao L. Agency set to track, deal with space junk. China Daily (Hong Kong ed.). 2015 Jun 10;Sect. "Constellations of Satellites".

²⁵ Robin McKie and MD. National: Warning of catastrophe from mass of 'space junk': Failure to act would be folly, says report to UN. The Observer. 2008 Feb 24;Sect. 25.

²⁶ United Nations, [Internet]. un.org; c2015. Space debris: orbiting debris threatens sustainable use of outer space.; 2008 [cited 2015 Aug 09]; Available from: <http://www.un.org/en/events/tenstories/08/spacedebris.shtml>

guidelines fostering the sustainable use of outer space, preventing pollution of the space environment. Such measures highlight how integral this issue is not only to scientists but also to the greater international community. The UN guidelines provide mitigation measures that include the planning, design, manufacture, and operations of spacecraft. Of great importance is limiting the longevity of spacecraft remaining in LEO well past their mission end date and removing them from this congested region. To date, these guidelines are voluntary, with no strict enforcement attached to them.²⁷

Enter the CubeSats and Small Sats

CubeSats are nanosatellites, a class of research spacecraft built with standardized dimensions (Units or “U”) of 10 cm × 10 cm × 11 cm. They can be 1U, 2U, 3U, or 6U in size and typically weigh less than 3 lbs per U.²⁸ NASA provides CubeSat developers with a low-cost path to conduct scientific investigations and technology demonstrations in space, enabling research for students and scientists. CubeSats are built from off-the-shelf components and mounted on a standardized frame. NASA’s CubeSats are deployed from a Poly-Picosatellite Orbital Deployer, or P-POD. Its CubeSat Launch initiative (CSLI) provides opportunities for small satellite payloads to fly on rockets planned for upcoming launches (see Fig. 4.6 on use of CubeSats by ISS).

The growing popularity of small satellites will increase the quantity of space junk and the probability of catastrophic collisions. To lessen the risk, current international guidelines suggest that CubeSats should be planned to have a maximum lifetime of 25 years, with some built-in method of deorbiting into the Earth’s atmosphere. “Some CubeSat operators are knowingly putting their craft into orbits that will last much longer than 25 years, with some as long as a hundred years,” says Hugh Lewis at the University of Southampton in the UK.²⁹

CubeSats have become more and more popular in the past decade. Hundred were launched between 2003 and 2012; another hundred were launched in 2013 alone. Lewis and his colleagues extrapolated these numbers in order to model what would happen if hundreds of CubeSats were launched every year for the next 30 years. Over time, the CubeSats would come within 10 mi of other spacecraft as

²⁷ United Nations, [Internet]. [un.org](http://www.un.org); c2015. Space debris: orbiting debris threatens sustainable use of outer space.; [cited 2015 Aug 09]; Available from: <http://www.un.org/en/events/tenstories/08/spacedebris.shtml>

²⁸ NASA, [Internet]. [nasa.gov](http://www.nasa.gov); c2017. Cubesats overview; [cited 2017 Oct 14]; Available from: https://www.nasa.gov/mission_pages/cubesats/overview

²⁹ Marks, Paul. 2014. CubeSat craze is recipe for disaster. *New Scientist*, 223(2988), 10.



Fig. 4.6. A set of NanoRacks CubeSats is photographed by an ISS crew member after the deployment by the NanoRacks Launcher attached to the end of the Japanese robotic arm. (February 25, 2014). Image Credit: NASA

many as 16 million times or more over three decades. There is some disagreement in the scientific community about the model parameters, but all agree that the CubeSat risk needs to be studied carefully. The first CubeSat collision occurred in 2013, resulting in the loss of Ecuador's first CubeSat. Smaller satellites the size of a circuit board, called Sprites, could be too small to be picked up by ground-based radar, presenting a tracking problem and an increased probability of collisions.³⁰

Constellations of Satellites

The companies OneWeb and SpaceX have plans to construct constellations of hundreds of satellites linked together, situated from low Earth to mid Earth orbit. OneWeb assures it will provide high-speed Internet access to the entire world by the end of the next decade, and it has recently expanded its plans to a network of more than 2000 satellites. SpaceX envisions a similar large constellation consisting of about 4500 satellites.

³⁰Marks, Paul. 2014. CubeSat craze is recipe for disaster. *New Scientist*, 223(2988), 10.

“If we have a 95% success rate with post-mission disposal and the lifetime of these disposal orbits is very short, we only have [26,000] new objects and 40–45 catastrophic collisions,” Lewis said. “In a situation without the constellation, we would have 37–38 catastrophic collisions, so that’s not such a big increase. However, the situation changes quite rapidly if the post-mission disposal success rate decreases.”³¹

As mentioned, current international guidelines recommend that satellites be removed from orbit within 25 years. But that isn’t fast enough, according to Lewis. “In our model, we could see that that the satellites that are on the decaying orbits of 25 years—they are actually interacting with the background population, and that’s where we see some of those impacts,” Lewis said.³² OneWeb, which expects to start launching its spacecraft next year, pledges that it will deorbit its satellites within 5 years from the end of their service.

Space Bounty

Legal issues surrounding space debris are plentiful. Under maritime law, any person or organization can remove an abandoned ship without the owner’s permission. This is not true for space vehicles, as stated in the 1967 Outer Space Treaty. “Once you put it up there, it is yours for life,” says James Dunstan, a lawyer specializing in space issues and founder of the Mobius Legal Group in Washington, DC. Thus, the US may not remove a Russian satellite from orbit even if that satellite was inoperative and was presenting a danger to working spacecraft.³³

Dunstan, along with the Progress and Freedom Foundation, a think-tank based in Washington, DC, has created an economic model that details how private industry might address the removal of space debris. An international body would set a base price. Private companies would be able to bid with satellite owners for the right to buy and de-orbit their spacecraft. Once the spacecraft is successfully deorbited, the company could receive a reward, funded by a new tax that satellite owners would have to pay. The alternative would be to set up a system to utilize valuable spacecraft materials. Dunstan estimates that there is a ton of material in

³¹ Pultarova, Leonard. [Internet]. [Space.com](https://www.space.com/36506-cubesats-space-junk-apocalypse.html); c2017. Could Cubesats trigger a space junk apocalypse?; April 19, 2017 [cited 2017 Oct 15]; Available from: <https://www.space.com/36506-cubesats-space-junk-apocalypse.html>

³² Pultarova, Leonard. [Internet]. [Space.com](https://www.space.com/36506-cubesats-space-junk-apocalypse.html); c2017. Could Cubesats trigger a space junk apocalypse?; April 19, 2017 [cited 2017 Oct 15]; Available from: <https://www.space.com/36506-cubesats-space-junk-apocalypse.html>

³³ Clark, Stuart. 2010. Who you gonna call? Junk busters!. *New Scientist*, 2017(2777), 46–49.

Earth orbit, including high-grade aluminium from discarded upper rocket stages. These empty fuel tanks could be rounded up to make an inexpensive space station or be used as protective materials to protect other satellites.³⁴

Reflections

Some experts think that we are approaching the Kessler syndrome stating that two objects that accidentally collide in space will generate more debris, which in turn collide with other objects and create more debris. The proliferation of orbiting projectiles continues until low Earth orbit is so full of debris that passage through it becomes impossible.³⁵ The Iridium and Kosmos satellite collision in 2009, as discussed in this chapter, can be seen as an early warning sign of the Kessler syndrome. The collision may have produced hundreds of thousands of smaller fragments, which cannot currently be tracked from Earth. A cascading collision of satellites in orbit would have disastrous effects on Earth, disrupting global communication and imaging while undermining national intelligence efforts.

The remains of past missions, such as useless rocket stages and lost astronaut equipment—some as small as a stray glove—have been left floating around. Bolts, lens caps, and a variety of small items either stay in orbit or re-enter the atmosphere and burn up. The only way to put a halt to the Kessler syndrome is to remove the ever-growing amount of objects from space, starting with those that are not working or are collision-resulting fragments.

There is a double-edged sword to the technology that might solve this issue, as anything that can be used to bring down unusable satellites can also bring down active ones. Such an object could be wielded as a weapon and have serious military implications. Yet, however you look at it and whatever the risks, it is clear that something has to be done to prevent outer space from becoming a garbage dump.

³⁴ Clark, Stuart. 2010. Who you gonna call? Junk busters!. *New Scientist*, 2017(2777), 46–49.

³⁵ Sommer M. UB researcher studying space junk. *Buffalo News*. 2014 Jan 19.



A Summary of the US Space Program and Its Relationship to the Military

“In no uncertain terms, space is a war fighting domain, not because we want it to be but because adversaries are threatening peaceful use.”

–Major General David Thompson, Vice Commander of the US Air Force Space Command. April 4, 2017¹

Introduction

In order to appreciate the full story of the current and future uses of outer space, it is necessary to reflect on the history of space exploration and the relationship between NASA and the US military.

This chapter details the evolution of politics and rockets during the US–USSR Space Race that culminated in the US landing on the Moon. The continued efforts of both countries post-Moon landing have created an enormous repository of scientific data about the environment of space along with technical advances to spy and disrupt spacecraft.

¹ Koren, Marina. [Internet] The Atlantic. America’s space commanders rattle their lightsabers. 05 Apr 2017; Sputnik; [cited 2017 Sep 08]. Available from: <https://www.theatlantic.com/science/archive/2017/04/space-war/521910/>

The Space Race: The Early History of Military Use of Space

The story of spaceflight and military conflicts are intertwined in history, starting with the development of rockets in World War II and ending with the Cold War and the Space Race. The Soviet Union was an ally to America during World War II, fighting together against their common opponent, Nazi Germany. In early 1945, Churchill, Roosevelt, and Stalin gathered together to establish post-war conditions as well as to promote international peace through the proposed United Nations. Just a few months later, the US displayed its state-of-the-art, deadly force against Japan by dropping atomic bombs on two of its major cities, virtually ending the war. Despite the Soviet Union possessing its own tremendous assets such as manpower, it became obvious to Stalin that the Soviet Union lagged behind the United States in weapons capability. Thus, by the end of 1945, the Cold War had begun.²

As part of the settlement agreement when Nazi Germany surrendered, rocket scientists working at the German rocket facility at Peenemünde were sent either to the United States or the Soviet Union. The German rocket scientists, including famous scientist and engineer Werner von Braun, had developed V-2 rockets, the most sophisticated missile and warhead delivery system at the time. Von Braun's dream to work on manned spaceflight was delayed as he and his colleagues' skills were directed towards the development of military systems instead. Von Braun and over one hundred German scientists went to the United States to begin developing missile technology using V-2 spare parts. In 1946, the newer version of the V-2 was launched, this time in peace and with instrumentation to study Earth's upper atmosphere.³ Due to the outbreak of the Korean War in the early 1950s, the military focus remained on ballistic missile development. Von Braun was selected to direct the ballistic weapons program of the US Army, focusing his labors on developing the medium-range Redstone ballistic missile and the intermediate-range Jupiter ballistic missile.⁴

Over the next several years, the United States and the Soviet Union independently developed their military capabilities, including nuclear bombs and missile delivery systems. Much of this work was accomplished in secret, at the same time as a series of escalating and aggressive actions taken by both countries caused increased political tensions. Scientists on both sides had interest in launching satellites into Earth orbit and using rockets for space exploration. However, military advantage took precedence over scientific space efforts. As early as the mid-1940s, American proposals to launch a satellite into orbit were met with a lukewarm reception. In 1946, the US Army Air Corps funded the Douglas Aircraft Company's

²Historylearning.com Staff. [Internet] Historylearningsite.co.uk; c2015. 1945-1950; [cited 2015 Sep 05]. Available from: <http://www.historylearningsite.co.uk/modern-world-history-1918-to-1980/the-cold-war/1945-1950/>

³National Aviation Hall of Fame. [Internet] nationalaviation.org; c2011. Wernher Von Braun. [cited 2015 Sep 02]. Available from: <http://www.nationalaviation.org/von-braun-wernher/>

⁴National Aviation Hall of Fame. [Internet] nationalaviation.org; c2011. Wernher Von Braun. [cited 2015 Sep 02]. Available from: <http://www.nationalaviation.org/von-braun-wernher/>

Project RAND (Research and Development) to perform a feasibility study on the development and proposed military uses of an Earth-orbiting satellite.⁵ The resulting report predicted that “The achievement of a satellite craft by the United States would inflame the imagination of mankind, and would probably produce repercussions in the world comparable to the explosion of the atomic bomb.”⁶ President Truman was not interested in developing space systems and instead preferred aeronautical research, even though the US Navy and Army Air Force expressed interest in satellite development for military purposes. Consequently, no space developments followed the RAND study, leaving the US trailing the Soviet Union and its secret development of Earth-orbiting satellites and an adapted missile launch system.⁷

The Soviet Union ballistic missile program followed a similar path to the United States after the surrender of scientists and engineers at Peenemünde, as German scientists began coordinating and working with Soviet rocket engineers. Sergei Korolev led the Soviet space accomplishments of the 1950s and 1960s, combining his abilities with the Germans to develop a V-2 replica, first launched in 1947. Korolev received very little support for his satellite work.⁸ At that time, Soviet attention was on the development of ballistic missiles and achieving military advantage over the United States. Later, in the 1950s, the escalating Cold War brought the United States to the brink of nuclear war with the Soviet Union.⁹

Satellite development in both countries was boosted by several famous international scientists interested in studying the Earth’s upper atmosphere in the early 1950s. James van Allen led a group of American scientists working on an international program to study the upper atmosphere using a variety of methods. At the same time, the US Department of Defense was also interested in rocketry and upper atmospheric sciences research, but with more of a focus on achieving national leadership in science and technology. The International Geophysical Year (IGY), a year-long period of intense solar activity starting in July 1957, provided a perfect opportunity for 67 different nations to study the space environment. During this time, in 1954, the US submitted a proposal to launch an artificial satellite into orbit. The Soviet Union did not have any submissions and was caught off guard by the US proposal. Nevertheless, the Soviets were ready to focus more intently on space exploration in order to keep pace technologically.¹⁰

⁵Kalic, Sean N. *US presidents and the militarization of space, 1946-1967*. College Station, Tx: Texas A&M University Press; 2012. 224 p.

⁶Aeronautics and Space Engineering Board, Division on Engineering and Physical Sciences. *Forging the future of space science: the next 60 years*. National Research Council; 2010. 166p.

⁷Kalic, Sean N. *US presidents and the militarization of space, 1946-1967*. College Station, Tx: Texas A&M University Press; 2012. 224 p.

⁸Dawson, L. *The Politics and Perils of Space exploration*. Springer Praxis Books; 2016. Chapter 6, Politics and the Space Race; p. 107–126.

⁹Zak, Anatoly. Sep 2003. The rest of the rocket scientists. *Air & Space Magazine*.

¹⁰Siddiqi, Asif A. [Internet] *History.NASA.gov*; c2015. Korolev, Sputnik, and the International Geophysical Year; [cited 2015 Sep 07]. Available from: <http://history.nasa.gov/sputnik/siddiqi.html>

In mid-1955, President Eisenhower announced that the United States was preparing to launch small Earth-orbiting satellites as a participation exercise for the IGY. The Soviets soon thereafter stated their intention to launch an artificial Earth satellite within 2 years. Both announcements garnered worldwide attention.¹¹ Tensions grew between the US and the USSR through the mid-1950s. Nikita Khrushchev was a rising political star in the Communist Party and eventually became Premier in 1958.¹² The Soviet Union and the US represented conflicting ideologies, and both sides were willing to take aggressive steps to ensure victory. Yet because both countries had nuclear weapons capability and the methods necessary to deliver it, the leaders concluded that peaceful coexistence was a better choice than war. Advancements in science, technology, and space exploration would thus have to suffice as symbolic measures of superiority for each nation.

On October 4, 1957, the Soviet Union launched the world's first artificial satellite, Sputnik I (see Fig. 5.1) into orbit. The mission was a success and shocked the rest of the world. US scientists were crushed that they were now behind the Soviets in a demonstration of science and technology in outer space. The world forever changed after the Sputnik launch. The satellite's recognizable *beep-beep-beep* signal was heard around the world, painfully reminding Americans that they could no longer claim that their capitalist, democratic republic was superior to the communist Soviet Union.¹³ In addition, they realized that the Soviets' ability to put Sputnik into orbit also meant that they had the capability to launch ballistic missiles that could carry nuclear or conventional weapons to attack other countries.¹⁴

In light of these events, US government officials re-evaluated their political priorities. The Eisenhower Administration found itself in hot waters for dismissing the significance of space in favor of military advancements. President Eisenhower still thought that Sputnik was just a cheap demonstration without any real substance, but he was now obligated to re-examine his tactics to achieve American supremacy. The United States now trailed the Soviet Union, a position that directly challenged Eisenhower's leadership.¹⁵

The US Defense Department granted simultaneous funding for both the Vanguard and the Explorer project, led by Werher von Braun's Army Redstone Arsenal team. The Explorer I rocket was successfully launched by the end of

¹¹ Siddiqi, Asif A. [Internet] History.NASA.gov; c2015. Korolev, Sputnik, and the International Geophysical Year; [cited 2015 Sep 07]. Available from: <http://history.nasa.gov/sputnik/siddiqi.html>

¹² Global Security Staff. [Internet] globalsecurity.org; c2015. 1955-1964—Kruschev; [cited 2015 Sep 08]. Available from: <http://www.globalsecurity.org/military/world/russia/khrushchev.htm>

¹³ Chalmers M Roberts, Staff Reporter. 1957. Sputnik healthily destroyed some illusions. The Washington Post and Times Herald (1954-1959);1.

¹⁴ L. Dawson. The Politics and Perils of Space Exploration. Springer International Publishing; 2017. Chapter 6, Politics and the Space Race; p. 107–126.

¹⁵ Mieczkowski, Yanek. Eisenhower's Sputnik moment: the race for space and world prestige. Ithaca, New York: Cornell University Press; 2013. 368p.



Fig. 5.1. A full-scale mock-up of the Sputnik 1 spacecraft on display at the Paris Air Show, 1975. Image Credit: NASA

January, 1958. It carried a satellite with a small scientific payload onboard, used to measure magnetic radiation in space. On October 1, 1958, Congress created the National Aeronautics and Space Administration (NASA) from the National Advisory Committee for Aeronautics (NACA) and other government agencies. NASA launched a series of Explorer spacecraft, continuing on with a variety of scientific experiments.¹⁶

Both the United States and the Soviet Union were now invested in outer space missions. President Eisenhower was interested in collaborating with the Soviets, believing that such a coalition could ensure that space would be utilized for peaceful pursuits. However, Khrushchev was not interested in the alliance. The US pursued a basic legal structure for peaceful space activities, a framework that eventually led to the creation of the Outer Space Treaty of 1967.¹⁷

¹⁶ Coldwar Org Staff. [Internet] coldwar.org; c2015. Sputnik; [cited 2015 Sep 08]. Available from: <http://www.coldwar.org/articles/50s/sputnik.asp>

¹⁷ Dawson, L. The Politics and Perils of Space Exploration. Springer International Publishing; 2017. Chapter 6, Politics and the Space Race; p. 107–126.

The Soviet space program then turned its attention on travel to the Moon, first through unmanned probes. In January 1959, the USSR's Luna 1 becomes the first manmade object to orbit the Sun, leading to Luna 2 in September, which intentionally crashed into the Moon, and Luna 3 in October, which orbited the Moon and photographed its surface. The US Pioneer 4 successfully conducted a Moon flyby in March 1959. Eisenhower's focus seemed unaffected by these developments, as space missions did not enhance the nation's security and were expensive without obvious payback. Thus, he endorsed scientific experimentation with specific intentions over voyages of outer space exploration.¹⁸

NASA established the first manned space program called Project Mercury in late 1958. The purpose was to determine human capability to live and work in space. NASA made several organizational changes in order to integrate efforts for NASA's long-term planning for Moon missions, a progression that occurred after Project Mercury. The Pioneer and Vanguard, as well as the Army Ballistic Missile Agency with its Saturn rocket programs, were moved under the guidance of NASA.

Many scientists opposed the fast approach required by the self-imposed Space Race. A 1958 report to the President from his Science Advisory Committee stated that some of the most prominent American scientists were more interested in the importance of science related to Earth, rather than space competitions with the Soviet Union. Scientists also felt that pursuing space science could weaken scientific efforts in other areas. Because of escalating events with the Soviets, a more balanced science budget did not pass.¹⁹

In 1959, NASA selected seven astronauts for the manned program Mercury. Meanwhile, Korolev was planning on launching a series of Vostok spacecraft capable of putting the first Soviets into orbit by 1961.²⁰

Eisenhower's Vice President Richard Nixon was defeated by John F. Kennedy in the US presidential election of 1960. Even though Eisenhower did not appreciate costly space efforts, the organizational structure for NASA that he put in place did make the race to the Moon go more efficiently. President Kennedy tried to promote collaboration with the Soviets. In his inaugural speech, he said, "Let both sides seek to invoke the wonders of science instead of its terrors. Together let us explore the stars."²¹

¹⁸ Planetary Staff. [Internet] planetary.org; c2015. Sputnik; [cited 2015 Sep 08]. Available from: <http://www.planetary.org/explore/space-topics/space-missions/missions-to-the-moon.html#pioneerp3>

¹⁹ Madrigal, Alexis. [Internet]. theatlantic.com; c2015. Moondoggle: the forgotten opposition to the Apollo program. Sep 12, 2012. The Atlantic—Technology. [cited 2015 Sep 09]; Available from: <http://www.theatlantic.com/technology/archive/2012/09/moondoggle-the-forgotten-opposition-to-the-apollo-program/262254/>

²⁰ Staff. [Internet] [Au.af.mil](http://au.af.mil); c2015. Eisenhower years: 1953-1960; [cited 2015 Sep 09]. Available from: <http://www.au.af.mil/au/awc/awcgate/au-18/au18003c.htm>

²¹ Sagdeev, Roald & Eisenhower, Susan. [Internet] NASA.gov; c2008; United States-Soviet space cooperation during the Cold War. [cited 2015 Sep 09]. Available from: http://www.nasa.gov/50th/50th_magazine/coldWarCoOp.html

The Soviet Union barrelled ahead. The USSR cosmonaut Yuri Gagarin was launched into space on April 12, 1961 and became the first human in outer space and orbiting the Earth. American Alan Shepard came next with his Mercury mission on May 2, followed by John Glenn's multi-orbital flight on February 20, 1962.²²

The American space program stayed one step behind the USSR for several years. Many of the firsts were taken by the Soviets: the first animal in orbit, first human in space, first woman in space, and first multi-person mission. More USSR firsts would include: commercial use of satellite, multi-person spacecraft flight, extravehicular activity, probe to orbit the Moon, probe to land on the Moon, and rendezvous and docking between crewed spacecraft.²³

In his first State of the Union address, President John F. Kennedy tasked the US space program with landing a man on the Moon before the decade's end. He was determined to overtake the Soviets in the Space Race, motivated by a growing sense of determination to prevent communism from spreading further. Kennedy's speech captured the motivation behind such an ambitious goal:

I believe this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to Earth. No single space project in this period will be more impressive to mankind, or more important in the long-range exploration of space; and none will be so difficult or expensive to accomplish.²⁴

Kennedy's bold political statement surprised NASA and the world. Funding and resources would have presidential support, but the effort would be risky. The Soviets were starkly aware of the challenge. NASA's efforts moved forward using Kennedy's speech as a guide. Project Mercury would follow with the multi-crew Gemini program, and finally the Apollo program, accomplishing the task of landing a crew on the Moon and bringing it safely back to Earth. The events leading to the landing on the Moon cannot be separated from a discussion of the Cold War. During this time, tensions between the US and the Soviet Union increased due to several significant events: the construction of the Berlin Wall in 1961, the Cuban Missile Crisis of 1962, and the outbreak of the war in Southeast Asia. Both countries edged closer to nuclear war more than once. A sense of resolve developed to complete the Kennedy dream, particularly after he was assassinated in November, 1963. President Lyndon Johnson, sworn in as President, worked toward Kennedy's promised Moon landing.²⁵

²² Sagdeev, Roald & Eisenhower, Susan. [Internet] [NASA.gov](http://www.nasa.gov); c2008; United States-Soviet space cooperation during the Cold War. [cited 2015 Sep 09]. Available from: http://www.nasa.gov/50th/50th_magazine/coldWarCoOp.html

²³ Braeunig, Robert. [Internet] [Braeunig.us](http://www.braeunig.us); c2011. Manned space flights; [cited 2015 Sep 09]. Available from: <http://www.braeunig.us/space/manned.htm>

²⁴ [NASA.gov](http://www.nasa.gov). [Internet] [NASA.gov](http://www.nasa.gov); c2014. NASA—excerpt from the 'special message to the congress on urgent national needs'; [cited 2015 Sep 09]. Available from: https://www.nasa.gov/vision/space/features/jfk_speech_text.html#.VfDorxFVhBc

²⁵ Dawson, L. *The Politics and Perils of Space Exploration*. Springer International Publishing; 2017. Chapter 6, Politics and the Space Race; p. 107–126.

Both Soviet cosmonauts and US astronauts lost their lives in pursuit of a successful landing on the Moon. The US at last overtook the USSR on July 20, 1969, when Apollo 11 commander Neil Armstrong became the first human to step onto the Moon's surface (see Fig. 5.2). The feeling in the Soviet Union was no doubt similar to the American sentiment when Yuri Gagarin became the first man in space.

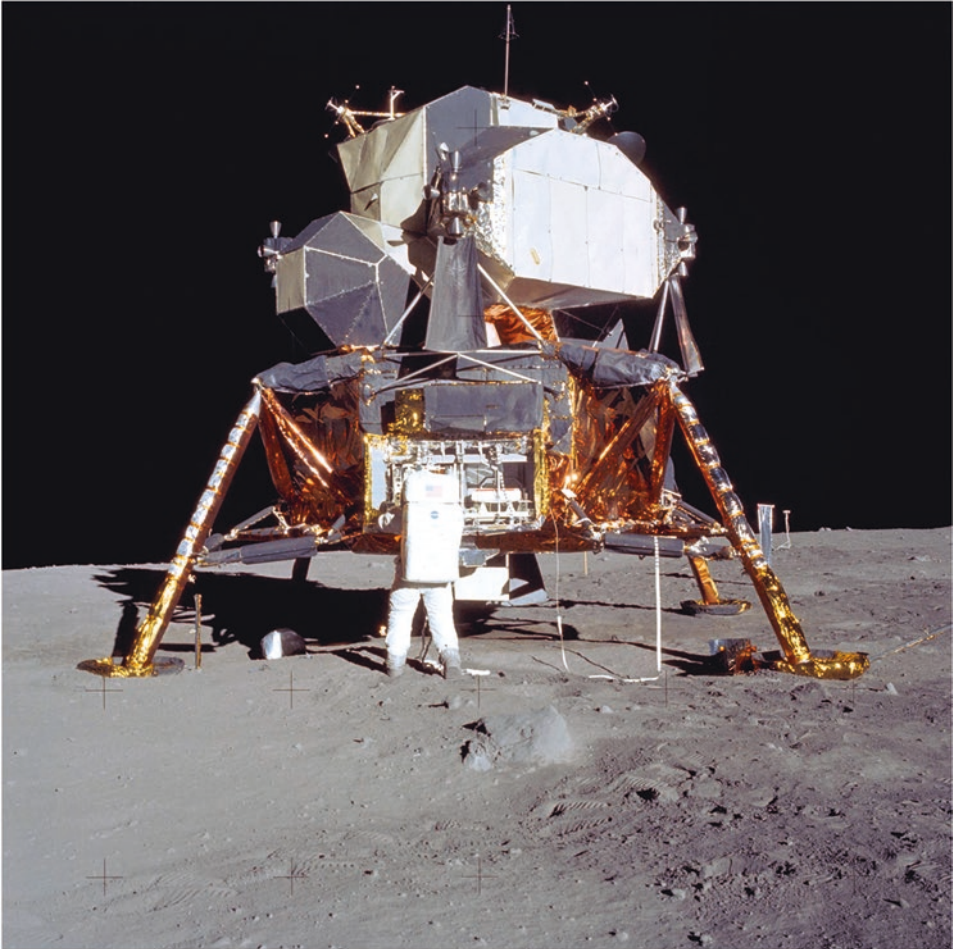


Fig. 5.2. Astronaut Buzz Aldrin prepares to deploy the experiment package during the Apollo 11 lunar surface extravehicular activity (EVA). July 20, 1969. Image Credit: NASA

Post-Apollo Space Efforts

By 1970, NASA was looking towards its post-Moon landing objectives, including the development of a space station and a reusable shuttle. The three final Moon landings were delayed past 1973–1974 in order for the Skylab space station to be

launched. NASA decided that Apollo 17 would be the last manned flight to the Moon, marking the end of an era.²⁶

The final Apollo mission took place in 1975. The remaining Apollo missions were cut due to budget restrictions imposed by Congress and the Nixon administration. Soon after the Moon landing, the desire to continue to travel to the Moon faded. The goal was accomplished, the tensions between the US and the Soviet Union had calmed down, and it was time to be more frugal with NASA's budget, which had increased to an all-time high in the 1960s. Now, NASA had plans for cuts, and there was a general desire to move on to other space exploration goals, rather than funding high risk manned missions. The close call with the Apollo 13 mission reminded everyone of the extreme dangers of spaceflight.²⁷

NASA's priorities turned to scientific research in Earth orbit. Two concepts competed for resources: a reusable space vehicle and a manned orbital laboratory. President Richard Nixon had established a Space Task Force in order to outline a number of objectives and priorities addressing the future of space exploration. Nixon wanted to carve out a legacy similar to what Kennedy had done with the Moon landing. The committee included recommendations to continue exploring outer space for peaceful purposes and to maintain a manned presence in missions in order to accomplish certain goals. The Task Force believed that the public still had a strong personal connection with manned space efforts, and it was important to continue including these efforts in addition to unmanned missions.²⁸

The Task Group looked ahead to a possible manned Mars mission in 15 years, but the pursuit of a Mars landing would usurp funds from scientific objectives. The recommendation was to land humans on Mars by the end of the twentieth century. This time frame passed with only a series of unmanned missions and probes sent to the red planet. These efforts were successful, but a manned mission still eluded NASA and government funding. Other Task Force recommendations included a series of both unmanned and manned programs to advance science and engineering and international relations for Earth's benefit. It was felt that it was equally important to look down on the Earth's surface from orbit to determine the health of the environment and atmospheric conditions as it was to look out beyond the Earth to increase our understanding of the Solar System and the universe. Plans were put in place for the development of a low-cost, reliable, and reusable space system that would include a transport vehicle. The vision included an operational space station constructed from modules with international cooperation. Scientific research and interests of international partners would be investigated on

²⁶ Silber, Kenneth. 16 July 2009. Down to Earth: the Apollo Moon missions that never were. *Scientific American*.

²⁷ Silber, Kenneth. 16 July 2009. Down to Earth: the Apollo Moon missions that never were. *Scientific American*.

²⁸ [NASA.gov](https://history.nasa.gov/SP-4407/vol1/chapter3-3.pdf). [Internet] Report of the Task Force on Space. Jan 08 1969. [cited 2017 Sep 09]. Available from: <https://history.nasa.gov/SP-4407/vol1/chapter3-3.pdf>

the space station for a long time in the future. The station would also provide a test bed to study the effects of long-term human presence in outer space.²⁹

President Nixon accepted the recommendations of the report and outlined six main objectives for NASA:

1. Continue to explore the Moon with focus on scientific discovery
2. Launch a series of satellites in Earth orbit to study Earth, the universe, and the Solar System. Send unmanned spacecraft to all planets in our Solar System, including landing vehicles on Mars, with the long-term goal being to launch human exploration efforts to Mars
3. Develop cheaper, multi-use, reusable vehicles, such as space shuttles, in order to reduce the cost of space exploration and operations.
4. Study the human ability to live and work in space for extended periods of time through a large Earth-orbiting laboratory called the Experimental Space Station. The long-term goal was to develop a multipurpose platform that serving as a springboard for interplanetary flight.
5. Develop space-related technology to include meteorology, navigation, national defense, and communications applications. Use satellite platforms to assess the Earth's environment and resources.
6. Seek international cooperation for space efforts in order to combine resources and achieve a faster result for the benefit of multiple nations.³⁰

Nixon's dominant message was to cut back large-scale expensive space plans. Apollo missions 18 through 20 were cancelled, but the space station Skylab mission and the Space Shuttle both survived. The President concluded that the United States could not afford to cut back its space program and lose an international edge in space technology and research. The Space Shuttle provided a perfect balance of manned scientific missions that offered a practical benefit for the space program. The cost of space travel would be lowered with the use of a mostly reusable spacecraft. The Space Shuttle was approved by a slight margin by Congress in 1972.³¹

²⁹ Space Task Group (US). The Post-Apollo space program: directions for the future. [Internet] History Office, NASA Headquarters, Washington, D.C.; 1969 [cited 2015 Sep 21]. Available from: <http://www.hq.nasa.gov/office/pao/History/taskgrp.html>

³⁰ Whittington, Mark. [Internet] *Examiner.com*. The 1969 space task group and why it failed to chart a post-Apollo space program. [cited 2016 Feb 20]. Available from: <http://www.examiner.com/article/the-1969-space-task-group-and-why-it-failed-to-chart-a-post-apollo-space-program>

³¹ Follett, Andrew. [Internet] College of William and Mary. 06 2013. The wrong right stuff: why NASA consistently fails at Congress. [cited 2018 Jul 22]. Available from: <https://scholar-works.wm.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1593&context=honorsthesis>

NASA had lobbied to preserve American superiority in space. Nixon decided that the space program should be considered on the same level as other domestic programs and needs, with no additional advantages. Human spaceflight beyond LEO would not be pursued because of the substantial financial investment. The Space Shuttle would be the primary post-Apollo NASA program developed, but its specific goals and long-term strategy remained unclear.³²

President Nixon's "Space Doctrine," outlined in 1970, detailed the policies that have remained at the core of US space policy to this day. His strategy was to cut spending and fund low-cost research efforts and space projects. In 1972, Nixon announced the funding of the Shuttle Program, setting the path for the future of space exploration. A lack of vision would plague the space program for decades. Desires for human travel outside of the Earth's orbit and to Mars were shelved for over 40 years due to insufficient resources and lack of interest, both in the government and among the public.³³

Space Stations

Any potential space station plans by NASA needed to be affordable. In the early 1960s, at Marshall Space Flight Center, Wernher von Braun proposed a large Earth-orbiting station, from which spacecraft traveling to the Moon or beyond could be launched. Apollo used a lunar orbit rendezvous, cutting off the Earth-orbiting operations. Space stations were relegated to future studies that aimed to identify a proper place for them in the space program.³⁴ Several categories of space station designs were proposed, some of them big and complex, generating artificial gravity through centrifugal forces of a rotating station. NASA defined the purpose and plans for an Earth-orbiting laboratory by the middle of 1963. The early missions would study humans working and living in space under weightless conditions for extended periods of time. An onboard manned laboratory would be used for research and experiments that would focus both on Earth resources and issues and out into space.³⁵

³² Logsdon, John M. *After Apollo? Richard Nixon and the American space program*. NY: Palgrave Macmillan; 2015. 368 p.

³³ Logsdon, John M. *After Apollo? Richard Nixon and the American space program*. NY: Palgrave Macmillan; 2015. 368 p.

³⁴ Compton, W. David and Benson, Charles D. *The NASA History Series*. [Internet] history. nasa.gov; SP-4208 Living and working in space: a history of Skylab; [cited 2015 Sep 22]. Available from: <http://history.nasa.gov/SP-4208/ch1.htm>

³⁵ Compton, W. David and Benson, Charles D. *The NASA History Series*. [Internet] history. nasa.gov; SP-4208 Living and working in space: a history of Skylab; [cited 2015 Sep 22]. Available from: <http://history.nasa.gov/SP-4208/ch1.htm>

The proposals for complex, large, or rotating space stations were rejected as too expensive, especially as there were no convincing reasons for making such a large station. Von Braun argued that NASA was not invested in planning for long-term space exploration. NASA's budget for the station was reduced in 1964, and the future of a medium or larger space station was put in jeopardy. Ambitions were redefined, aiming instead for an extension of the Apollo program as an Earth-orbiting laboratory. At the same time, the Air Force began showing interest in an orbiting laboratory, which was viewed as Skylab's competitor.³⁶

The US Air Force vs. NASA

In the mid to late 1960s, the US Air Force expressed interest in the construction of a Manned Orbiting Laboratory (MOL) as a top-secret project. The Air Force proposed that up to four military crewmembers work and stay in a space module for extended periods of time. The orbiting laboratory's use was touted as scientific in nature, but secretly, the station would provide a reconnaissance window to Soviet activities and military applications in space. A pressurized module the size of a van would be connected to a modified Gemini capsule and launched into low Earth orbit using a military Titan III rocket.³⁷

The Air Force was willing to have NASA be responsible for the design and development work needed to transport the military astronauts to their Manned Orbiting Laboratory (MOL). NASA ended up in a support role, as the Air Force developed most of the project. Three modules were planned for earth science study, astronomy, and testing space systems. The MOL had an equatorial orbit that prevented it from passing over the Soviet Union, eliminating the reconnaissance mission goal unless orbital changes were made. As the MOL was in development, the costs of President Johnson's domestic programs and the ongoing Vietnam War took priority over government funding. In 1968, the Air Force's budget was slashed. The US went into a recession, and the amount of available money dropped yet again. Future space programs couldn't survive while the war continued to use up the military budget. Soon, the MOL program was cancelled altogether,³⁸ for reasons that will be addressed in the following section.

³⁶ Compton, W. David and Benson, Charles D. The NASA History Series. [Internet] history. nasa.gov; SP-4208 Living and working in space: a history of Skylab; 1983. [cited 2015 Sep 22]. Available from: <http://history.nasa.gov/SP-4208/ch1.htm>

³⁷ Dorr, Robert F. [Internet]. [Defensemmedianetwork.com](http://www.defensemmedianetwork.com); Air Force Manned Orbiting Laboratory (MOL) astronauts would have conducted surveillance and scientific research; Oct 19, 2011 [cited 2015 Sep 23]; Available from: <http://www.defensemmedianetwork.com/stories/what-might-have-been-manned-orbiting-laboratory-mol/>

³⁸ Dorr, Robert F. [Internet]. [Defensemmedianetwork.com](http://www.defensemmedianetwork.com); Air Force Manned Orbiting Laboratory (MOL) astronauts would have conducted surveillance and scientific research; Oct 19, 2011 [cited 2015 Sep 23]; Available from: <http://www.defensemmedianetwork.com/stories/what-might-have-been-manned-orbiting-laboratory-mol/>

Skylab

In the early 1960s, NASA was developing a small, efficient space station in LEO designed to utilize surplus rockets and space hardware from earlier Gemini and Apollo missions. The “Apollo Applications Project” would use an empty Saturn V upper stage as a base module that Apollo command modules could dock with (see Fig. 5.3). The station, called Skylab, would be used to study the Earth and the long-term effects of space travel. Skylab became a lower priority than Apollo until at least the first Moon landing was completed. The program did not have the same level of funding as Apollo, however, NASA believed it was important to look beyond the Moon landing to future projects that could benefit America and preserve the country’s leadership in space. Even though national support dropped after

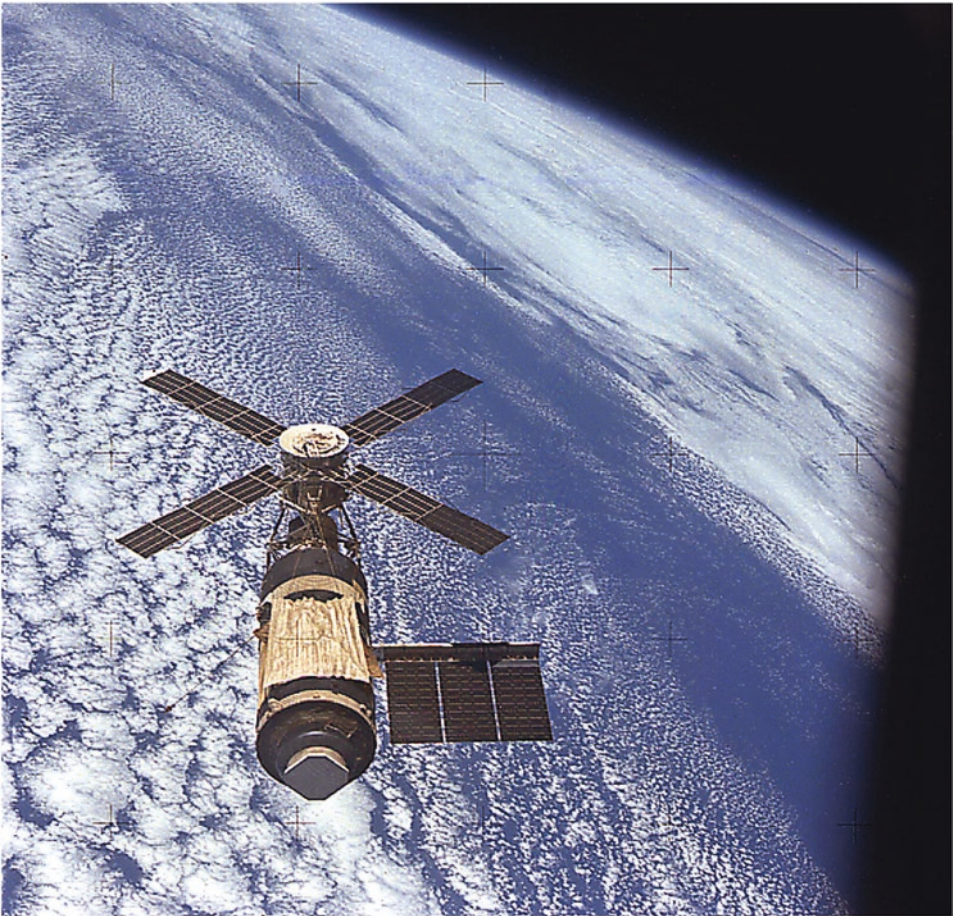


Fig. 5.3. Skylab design of a spent Saturn upper stage as an orbital workshop, launched in May 1973. Image Credit: NASA

the Moon landing, NASA still felt that Skylab would help the US retain a presence in manned spaceflight while studying humans living and working in space.³⁹

Congress didn't want to fund Skylab, so the Air Force stepped in. The Air Force was already working on the top secret MOL project, which originally was planned to carry out long-term surveillance missions on the Soviet Union. MOL's missions could be combined with the upcoming Space Shuttle's plans.⁴⁰ The NASA Skylab plans also offered a much larger platform with more sophisticated equipment, so it was thought that the MOL and Skylab could be combined. Thus, Skylab was given the green light.⁴¹

By 1971, the Air Force switched its plans away from a space station and decided that camera and surveillance equipment would be more flexible if deployed on unmanned satellites operating in polar orbits. Thus, the MOL program was cancelled. Skylab continued without military funding and was launched in May 1973. Skylab continued operating successfully for several years before it was deliberately de-orbited with a safe re-entry burn.⁴²

Because of the success of the Skylab missions, NASA thought that the Skylab concept could be converted into a much larger, permanently manned Space Station supplied by the Space Shuttle. The proposed Space Station could also serve as a springboard to Mars. Politics once again set the agenda. In 1972, President Nixon announced that the Space Shuttle would be funded, but the Space Station would not be. Consequently, the Space Shuttle was left without a clear-cut mission, something that would affect its legacy over the next four decades.⁴³

³⁹Compton, W. David and Benson, Charles D. The NASA History Series. [Internet] history. nasa.gov; SP-4208 Living and working in space: a history of Skylab; 1983. [cited 2015 Sep 24]. Available from: <http://articles.adsabs.harvard.edu/full/seri/NASSP/4208/0000001,004.html>

⁴⁰Wordpress Staff. [Internet] wordpress.com; False steps: the Space Race as it might have been; the manned orbiting laboratory: a USAF space station; July 15, 2012. [cited 2015 Sep 24]. Available from: <https://falsesteps.wordpress.com/2012/07/15/the-manned-orbiting-laboratory-a-usaf-space-station/>

⁴¹Compton, W. David and Benson, Charles D. The NASA History Series. [Internet] history. nasa.gov; SP-4208 Living and working in space: a history of Skylab; 1983. [cited 2015 Sep 24]. Available from: <http://articles.adsabs.harvard.edu/full/seri/NASSP/4208/0000001,004.html>

⁴²Flink, Lenny. [Internet] Dailykos.com; The sky is falling: the life and death of Skylab; Apr 16, 2014 [cited 2015 Sep 24]; Available from: <http://www.dailykos.com/story/2014/04/16/1250880/-The-Sky-is-Falling-The-Life-and-Death-of-Skylab>

⁴³Flink, Lenny. [Internet] Dailykos.com; The sky is falling: the life and death of Skylab; Apr 16, 2014 [cited 2015 Sep 24]; Available from: <http://www.dailykos.com/story/2014/04/16/1250880/-The-Sky-is-Falling-The-Life-and-Death-of-Skylab>

The Space Shuttle

After the Apollo program in the late 1960s, NASA strove to maintain America's position as a leader in space. A reusable Space Shuttle vehicle was proposed as a low-cost, manned transportation vehicle that would operate between the surface of the Earth and LEO, docking with a manned space station (an updated, bigger, and more permanent version of Skylab). It became obvious in 1970 that NASA would not be funded for both the Shuttle and a space station. NASA thought that the Space Shuttle stood a better chance of funding, therefore, it turned its focus to the development of the Shuttle program. As always, the future of space exploration was shaped by available capital.

The Space Shuttle design was tied to cost estimates, and drastic changes had to be made to afford the program. In early 1972, President Nixon approved the development of the Space Shuttle in order for the US to remain a global leader in space for both manned and unmanned missions throughout the 1980s and beyond. However, the Shuttle's capabilities remained limited under budgetary constraints. The original goal of having a vehicle system that was 100% reusable was never achieved. The solid rocket boosters were refurbished and reused, but the external fuel tank was discarded and not recovered from the ocean.

Government funding and NASA's space exploration goals once again were tied together. The tight Shuttle budget resulted in a program that is criticized to this day for its lack of vision. The Space Shuttle was going to be the transport system that supported the International Space Station. When the space station wasn't fully in place until the end of the Shuttle era, this vision ended up out of sequence. The Shuttle program ended before the ISS could make full use of it, leaving the US to depend on Soviet spacecraft to transport crews and supply the station.⁴⁴ The Shuttle operated for 30 years, from 1981 to 2011.⁴⁵

The Shuttle system proved that a partially reusable vehicle could be designed with the ability to enter orbit, perform routine space tasks such as delivering and repairing satellites, and rendezvous with the Space Station in order to deliver astronauts and supplies. As mentioned before, the Shuttle never became the totally reusable, cost-effective transportation system for launching payloads into Earth orbit.⁴⁶ Still, the Space Shuttle did build the ISS one piece at a time over a span of several years, starting in 1998 (Fig. 5.4).

⁴⁴Logsdon, John M. May 1986. The decision to develop the Space Shuttle. *Space Policy*. 2:2:103–119.

⁴⁵NASA.gov. [Internet] [NASA.gov](http://www.nasa.gov); Oct 10, 2004 [cited 2015 Nov 11]. Available from: http://www.nasa.gov/externalflash/the_shuttle/

⁴⁶Wall, Mike. [Internet]. [Space.com](http://www.space.com); c2012. Space Shuttle Discovery: 5 surprising facts about NASA's oldest orbiter.; April 19, 2012 [cited 2015 Nov 16]; Available from: <http://www.space.com/15330-space-shuttle-discovery-5-surprising-facts.html>

Some of the Space Shuttle's most significant accomplishments during its 30-year history include:

- 135 flights and over 1300 days in space
- 2300 experiments flown aboard, tested in microgravity
- Over 3.5 million pounds of cargo launched into orbit
- Almost 200,000 man-hours spent in space
- 355 individual astronauts and cosmonauts flown, hailing from 16 different countries
- 180 satellites and other payloads deployed (including components of the ISS)⁴⁷

The Space Shuttle provided a laboratory in microgravity to perform scientific research. Space Shuttle research was conducted primarily on the Spacelab module or other Spacelab experimental units placed in the orbiter payload bay. Further research could be performed on a much larger scale on the ISS. Microgravity research was conducted on Skylab, continued on the Space Shuttle, and expanded on the ISS with other experimentation.⁴⁸

The Spacelab Module

The Spacelab concept originated with the Space Task Group commissioned by President Nixon.

The rejection of NASA's first bid for a space station in the early 1970s gave rise to the alternative concept of the Spacelab module. NASA immediately modified the Research and Applications Modules (RAM)—modules that would enter orbit in the payload bay of the Space Shuttle, perform their functions as a standalone laboratory module, and return to Earth at the end of the Shuttle mission.⁴⁹ NASA offered Europe the opportunity to partner in a Spacelab collaboration, and discussions began between NASA and the two European space agencies of that time—the European Launcher Development Organization (ELDO) and the European Space Research Organization (ESRO). The organizations merged in 1975 to form the European Space Agency (ESA).⁵⁰

⁴⁷CBS.news. [Internet] cbsnews.com; Space Shuttle: 30 years of fascinating facts. July 21, 2011; [cited 2015 Nov 15]. Available from: <http://www.cbsnews.com/news/space-shuttle-30-years-of-fascinating-facts/>

⁴⁸Witze, Alexandra, Kenneth. 18 June 2011. Good-bye Shuttle: looking back at the space plane's scientific legacy. *Science News* Vol. 179. No. 13, pp. 20–21.

⁴⁹Walter Froehlich. The NASA History Series. [Internet] history.nasa.gov; EP-165 Spacelab: Chapter seven: Spacelab: its birth, its impact, its future living and working in space: a history of Skylab; 1983. [cited 2016 Feb 22]. Available from: <http://history.nasa.gov/EP-165/ch7.htm>

⁵⁰Waldrop, M. Mitchell. AAAS Science Archives 1983-1985. [Internet] Spacelab: science on the shuttle. [cited 2016 Feb 22]. Available from: http://www.ganino.com/games/Science/Science%201983-1985/root/data/Science_1983-1985/pdf/1983_v222_n4622/p4622_0405.pdf

The European nations agreed to develop a unique module/space laboratory that would utilize the Shuttle's capacity to carry out scientific research. Both the technology and funding required were within ESA's means. The international agreement was signed by ten European partners in August 1973 (nine partners initially, with Austria signing later). It was called the Spacelab Memorandum of Understanding (MOU), and it represented the first international technical and scientific cooperative agreement of such magnitude. It gave Europe the right to fund, design, build, and deliver Spacelab in exchange for a shared first mission aboard the Space Shuttle. In June 1974, the European Space Agency (ESA) selected an industrial consortium to develop the modular pieces to fit inside Spacelab, including a pressurized laboratory. The laboratory would provide the opportunities for businesses and universities to conduct a variety of research activities. Congress was already encouraging NASA to branch out into privatization and international partnerships to achieve common goals.⁵¹

The Spacelab project complex management procedures and system integration. The first Spacelab flight was planned to be a cooperative mission, with NASA and ESA both flying experiments of equivalent scale. Politics played a major role in establishing the conditions and criteria for the international team agreements and responsibilities.⁵² Spacelab was designed to fit into the Shuttle cargo bay and connect with the crew compartment, allowing scientists to work in a pressurized laboratory in a shirt-sleeve environment (see Fig. 5.5). In addition, unpressurized external pallets would provide research platforms for external data collection and research in fields of astronomy, studies of the Earth's atmosphere, and other observations. The lab was adaptable and reusable. It conducted hundreds of experiments in the microgravity environment of low Earth orbit.⁵³ The first flight of Spacelab took place aboard the Space Shuttle Columbia in 1983. It was the first time a citizen of another country flew as an astronaut on the US spacecraft.⁵⁴

Spacelab was an intermediate step in the development of the ISS, allowing NASA to achieve several scientific objectives with the financial backing of the European Space Agency (ESA). By 1972, NASA had already postponed the

⁵¹ NASA.gov. [Internet] NASA.gov; 2013 [cited 2015 Dec 29]. Available from: http://www.nasa.gov/sites/default/files/files/Spacelab_Collection_140117a.pdf

⁵² Walter Froehlich. The NASA History Series. [Internet] history.nasa.gov; EP-165 Spacelab: Chapter seven: Spacelab: its birth, its impact, its future living and working in space: a history of Skylab; 1983. [cited 2016 Feb 22]. Available from: <http://history.nasa.gov/EP-165/ch7.htm>

⁵³ NASA.gov. [Internet] NASA.gov; 2013 [cited 2015 Dec 29]. Available from: http://www.nasa.gov/sites/default/files/files/Spacelab_Collection_140117a.pdf

⁵⁴ Wilford, John Noble. 29 Nov 1983. Columbia carries spacelab to orbit with 6-man crew. The New York Times. [Internet] [cited 2016 Feb 23]. Available from: <http://www.nytimes.com/1983/11/29/us/columbia-carries-spacelab-to-orbit-with-6-man-crew.html?pagewanted=all>

development of a large space station due to its inability to fund both the Space Shuttle and a space station. Spacelab provided the opportunity to conduct space experiments in the interim.

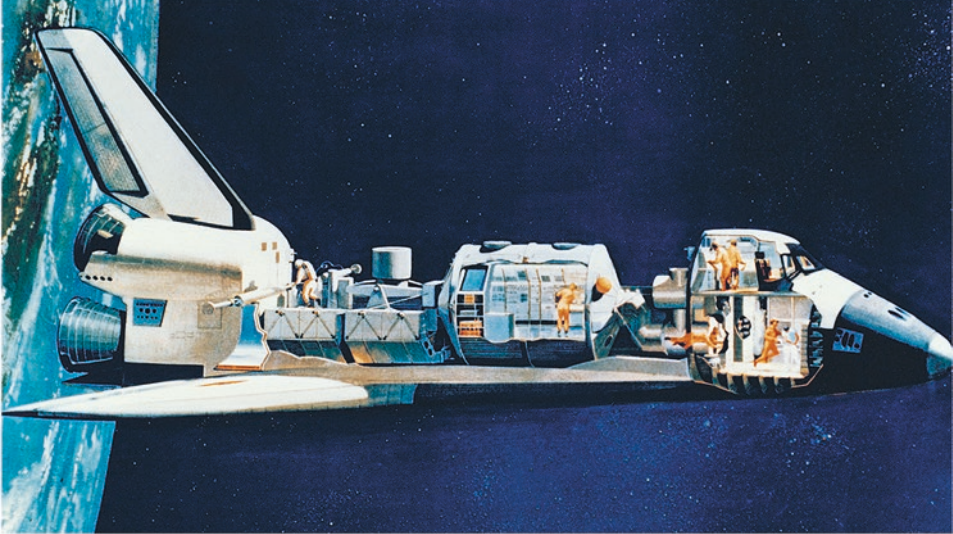


Fig. 5.5. An illustration of Spacelab. Image Credit: NASA

The Marshall Space Flight Center in Huntsville, Alabama, was responsible for the overall program planning and management of Spacelab, while the European Space Agency (ESA) designed and developed the module and pallets. Marshall became experienced in international space partnerships and missions, looking to the future and planning similar modules for an International Space Station.⁵⁵

Research accomplished in Spacelab through the Shuttle resulted in major discoveries in astronomy, biology, and crystallography. These experiments paved the way for more in-depth experimentation aboard the ISS.

The Military Influence on Space Shuttle Operations

The US Department of Defense (DOD) was interested in military applications for the Space Shuttle. The Air Force was tasked to work with NASA in developing the Shuttle system. The cargo bay of the Shuttle was designed to hold spy satellites,

⁵⁵ [NASA.gov](http://www.nasa.gov). [Internet] [NASA.gov](http://www.nasa.gov); 2013 [cited 2015 Dec 29]. Available from: http://www.nasa.gov/sites/default/files/files/Spacelab_Collection_140117a.pdf

and up until the Challenger disaster, the military was using the Shuttle's payload bay to transport surveillance equipment. Although NASA promoted the Space Shuttle as a civilian vehicle, the Department of Defense (DOD) agreed to support and partner with NASA for military operations in space, such as the use of reconnaissance and national security payloads in low Earth orbits. Political and financial support would be withheld unless NASA modified its design to support the military space program. For the DOD, the Space Shuttle could provide cheaper and more flexible options for military space operations.⁵⁶

Some proposed military missions required satellites to be launched to high-inclination orbits in order to survey regions of interest on Earth. Polar orbit was the destination for surveillance and imaging satellites. The location of the military launch facilities at California's Vandenberg Air Force Base was perfect for launching Shuttles over the ocean to reach the desired orbit, while launches from Florida's Cape Canaveral required the Shuttle to fly over populated land after launch. The US Air Force Space Shuttle era was supposed to begin in 1986, with astronaut Bob Crippen (first crew of the Space Shuttle) as commander of the first mission to polar orbit. The Shuttle would be carrying the Teal Ruby experimental satellite along with long-range sensors in the payload bay. Expectations for the Shuttle to be an integral part of military space operations were high. In order to prepare for these upcoming highly secret missions, between 1979 and 1986, the DOD trained 32 Navy and Air Force officers as military astronauts. In 1986, the DOD started a Military Man-in-Space Program to ensure a strong human military presence. The Air Force believed that experienced military astronaut judgment would be essential when dealing with complex situations.⁵⁷

Early in the Space Shuttle program, it was clear that multiple launches per year and fast turnaround times per launch would not be possible. The military re-examined its plans to use the Shuttle for military operations. It no longer seemed viable to hinge strict launch guidelines onto the Space Shuttle in order to transport military systems into space. The cost advantage over expendable launch vehicles was reassessed. The military examined whether the Shuttle could meet its demands as unmanned booster operations continued. Under Secretary of the Air Force and top-ranking military official "Pete" Aldridge was chosen to fly aboard the first Vandenberg Shuttle mission. Soon after the Challenger explosion, the Vandenberg Shuttle missions were cancelled, and the Pentagon focused on developing

⁵⁶ Dawson, L. *The Politics and Perils of Space Exploration*. Springer International Publishing; 2017. Chapter 6, Politics and the Space Race; p. 107–126.

⁵⁷ Ray, Justin. [Internet]. [Space.com](http://www.space.com/10644-california-launch-pad-history-shuttles-rockets.html); c2011. From Shuttles to rockets: long history for California launch pad; January 19, 2011 [cited 2015 Dec 30]; Available from: <http://www.space.com/10644-california-launch-pad-history-shuttles-rockets.html>

expendable rockets to deliver payloads. Only experiments requiring astronaut assistance were to fly aboard the Shuttle.⁵⁸

In the 1980s, the DOD proposed the development of a hypersonic space plane that could take off, fly into orbit, perform its mission, and return like an airplane. This vehicle would be a single-stage-to-orbit (SSTO) vehicle developed with NASA assistance and focused on military purposes. Defense Advanced Research Projects Agency (DARPA) funded the secret program between 1983 and 1985. The Reagan administration revealed it as the National Aerospace Plane, designated the X-30. The design was sophisticated and challenging, with a multitude of technical difficulties. The project ended in 1994 after billions were already spent. However, this type of vehicle, and the technological concepts behind this program, remain today an important component in military space defense and war capabilities. A military presence in space is still considered to be part of a strategy essential for national security.⁵⁹

Between 1982 and 1992, several Space Shuttle missions remained classified by the military. During that time, NASA launched 11 classified payloads, making changes in the cargo bay that were requested by the military. Only one of all of the trained military astronauts flew on the Shuttle—Gary Payton, who later became the Deputy Under Secretary of the Air Force for Space. Military payloads were launched successfully, and the associated mission requirements were satisfied.⁶⁰

The International Space Station

Once the Space Shuttle became operational in 1982, NASA started working on a conceptual design for a large manned space station, built over time and connecting individual modules that could fit in the payload bay. It would utilize the capabilities of the Space Shuttle and also serve as an intermediate base for outer space exploration, something that was never realized. Emphasis was placed on international cooperation, both technical and financial. NASA led the effort, asking Canada, US-friendly European countries, and Japan to contribute to the efforts.

⁵⁸ Ray, Justin. [Internet]. [Space.com](http://www.space.com/10644-california-launch-pad-history-shuttles-rockets.html); c2011. From Shuttles to rockets: long history for California launch pad; January 19, 2011 [cited 2015 Dec 30]; Available from: <http://www.space.com/10644-california-launch-pad-history-shuttles-rockets.html>

⁵⁹ Launius, Roger. [Internet]. [wordpress.com](https://launiusr.wordpress.com/2012/11/12/nasas-space-shuttle-and-the-department-of-defense/); c2012. NASA's Space Shuttle and the department of defense; Nov 12, 2012 [cited 2015 Dec 30]; Available from: <https://launiusr.wordpress.com/2012/11/12/nasas-space-shuttle-and-the-department-of-defense/>

⁶⁰ Cassutt, Michael. Air & Space Magazine, Secret Space Shuttles, August, 2009.

Some countries were already partners with NASA in developing aspects of the Shuttle. Canada developed the very successful remote manipulator arm, which was mounted in the payload bay of the orbiter and was designed to deploy and rescue satellites. ESA had already participated in the development of Spacelab, the manned space laboratory module that fit into the Shuttle cargo bay.

In 1984, President Reagan confirmed his support for the construction of a permanently manned Earth orbiting space station in his State of the Union address:

America has always been greatest when we dared to be great. We can reach for greatness again. We can follow our dreams to distant stars, living and working in space for peaceful, economic and scientific gain. Tonight, I am directing NASA to develop a permanently manned space station and to do it within a decade.⁶¹

The manned space station was advertised as a technological feat that could strengthen the economy, perform cutting-edge scientific research, and improve the overall quality of human life. By 1985, Japan, ESA, and Canada had decided to participate. The original space station was named Freedom. Although initially approved, it was never completed, as it underwent several cutbacks before evolving into the current International Space Station.⁶² The final International Space Station (ISS) became arguably one of the greatest technological achievements of humankind. Its assembly started in 1998, with construction lasting over a period of 15 years and requiring more than 30 missions to complete.⁶³

President George H.W. Bush outlined the construction of the Space Station Freedom in his 1989 Space Exploration Initiative, along with plans to return humans to the Moon, and future plans for manned missions to Mars. The new plans, estimated at approximately \$500 billion over 20–30 years, were opposed by the White House and Congress. President Bush sought out international partners, but the program still proved too expensive. In 1990, the President established the Advisory Committee on the Future of the Space Program to make recommendations to NASA. The Committee felt that NASA should focus on Earth and space science using robotic methods, essentially ending the development of any new manned missions. President Bush ordered NASA to go ahead with these recommendations. In 1996, President Clinton's Administration's National Space Policy altogether removed human exploration from the US national agenda.⁶⁴

⁶¹ Scimemi, Sam. NASA and the legacy of the International Space Station. NASA Advisory Council HEO Committee; July 29, 2013.

⁶² <https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-the-iss-58.html>

⁶³ <https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-the-iss-58.html>

⁶⁴ Dick, Steve. Summary of space exploration initiative. [cited 2016 Jan 18]. Available from: <http://history.nasa.gov/seisummary.htm>

Strong interest in a low Earth orbit manned space station was still strong. In 1993, President Clinton directed NASA to redesign the space station, replacing Freedom with a less expensive model. Congress voted to support the ISS by a narrow margin. President Clinton's administration partnered with Russia to help with ISS construction and transport of required items to the station.⁶⁵ Russia would participate with the US as a partner, providing parts along with technological and financial support. It is thought that Clinton included Russia as a valued participant in ISS development as a strategy in foreign policy. Russia's agreement to accept a formal ballistic missile proliferation policy happened almost simultaneously with the announcement identifying Russia as an equal partner with the US in the ISS operation and construction. Many US scientists, astronauts, and public and industry leaders opposed Russia's increased profile in the US space program. Their concerns were validated, as Russia ended up having problems satisfying its financial commitments. This was quite troubling, because the Russian module was the first critical module of the station. The module would provide life support for crews as well as propulsion and control for the orbital complex. This component was so delayed that NASA decided to build a US temporary module that could be put in place, allowing the plans to continue. In time, all of these issues were finally resolved, and the module was delivered.⁶⁶

International collaboration proved essential for the success of the ISS. Russia provided several more modules for the station, as well as the spacecraft to transport the crew and cargo into orbit. Russia's own space program could progress and be more financially stable without the burden of constructing its own space station. A Russian rocket launched the first piece of the ISS, and 2 years later, in 2000, the first crew arrived. Humans have continuously occupied the station ever since.⁶⁷

The ISS was an ambitious project. Many unpredicted issues concerning time and financial estimates arose, and cost overruns were inevitable. The station progressed in stages over the years, and construction wasn't officially completed until 2011 (Fig. 5.6).

⁶⁵ Smith, Marcia S. NASA's space station program: evolution and current status: Testimony before the house science committee; Apr 4, 2001. [cited 2016 Jan 18]. Available from: <http://history.nasa.gov/iss testimony2001.pdf>

⁶⁶ JAXA. Japan Aerospace Exploration Agency. May, 1999. [cited 2016 Jan 18]. Available from: http://iss.jaxa.jp/iss/history/index_e.html

⁶⁷ <https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-the-iss-58.html>

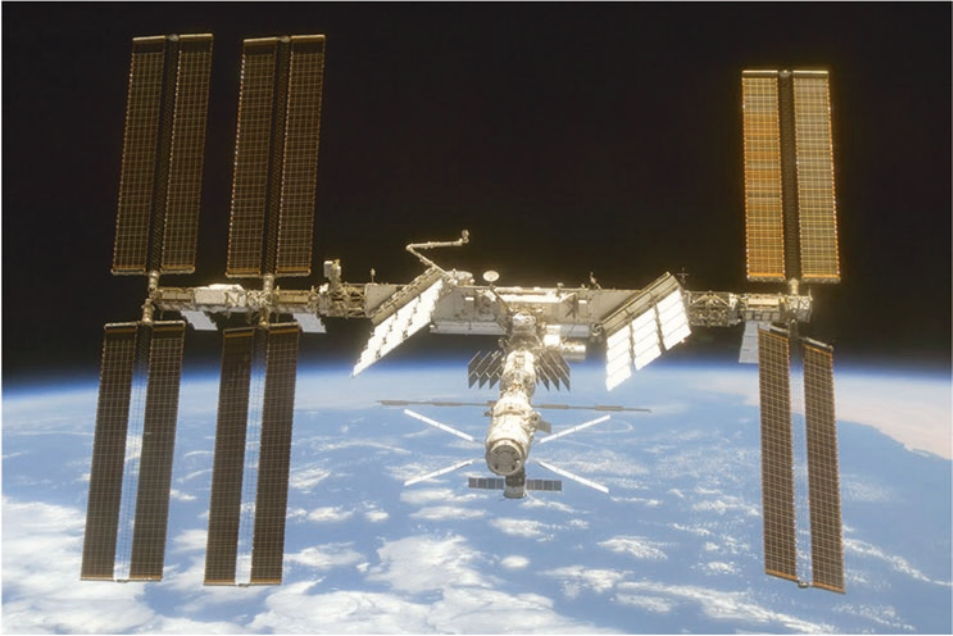


Fig. 5.6. The International Space Station (ISS). Image Credit: NASA

After 15 years of continuous operation (the original design milestone), the ISS addressed its continued funding along with the uncertainty of extending its operations until 2024. President Obama supported extending the ISS operations funding. However, financial support by international partners was uncertain. In order to keep the ISS functioning long term, critical systems had to be evaluated to determine what upgrades would be required. Most importantly, the retirement of the Space Shuttle program limited the US ability to deliver supplies, larger replacement parts, or transport and replace crew members. US astronauts had been ferried by the Russian Soyuz spacecraft, a controversial decision for NASA and individuals supporting the space program. For many, it was difficult to accept the program's reliance on Russia for the transport and safety of American crews, not to mention the cost—upwards of \$80 million to transport a single astronaut to the ISS.

Political tensions increased between the two nations as Russia came under the leadership of Prime Minister Vladimir Putin. When the situation calmed down in early 2015, the two countries agreed to build a new space station after the ISS finished its extended life in 2024. In addition to the space station agreement, Russia and the US agreed to cooperate on a NASA-led program to build the first lunar space station, building towards a long-term project to send humans to Mars. NASA's Chief Charles Bolden confirmed the partnership: "Our area of

cooperation will be Mars. We are discussing how best to use the resources, the finance, we are settling time frames and distributing efforts in order to avoid duplication.”⁶⁸

Reflections

The US and Russian space programs have been intertwined for decades, first in conflict and then, after the Moon landing, in cooperation and partnership. In the time of collaboration, the US freely purchased Russian engines and bought space on transport vehicles to supply the ISS with supplies and crew. When the Space Shuttle retired in July of 2011, NASA lost its ability to transport astronauts into space. The Orion Multi-Purpose Crew Vehicle will be the next NASA transport spacecraft, but it won't be ready for crewed missions until after 2021. In the interim, NASA's only option for ferrying crews is to pay for rides aboard Russia's Soyuz capsule. Now, private firms have expressed interest in developing such capabilities. Both SpaceX and Orbital Sciences won contracts through NASA to develop vehicles to transport cargo to the ISS and provide LEO access for a lower cost. NASA can now focus on deep-space exploration and more far-reaching objectives. In 2014, NASA Administrator Charles Bolden announced that Boeing and SpaceX will build the first private vehicles (Boeing CST-100 and SpaceX Dragon V2) for the purpose of launching American astronauts to the ISS, restoring the capability to launch crews from American soil for the first time since 2011.⁶⁹

Historically, most of NASA's budget was paid to private contractors to design and build space vehicles, rockets, and other equipment. NASA provided oversight, management, and operations of the overall projects. Now, NASA can privatize some of the operations that focus on transport and LEO activities. This shift is an important one affecting the future of NASA. Some experts debate whether or not private industry can handle the complexity and safety requirements of manned spaceflight beyond low Earth orbit. What is certain is that the future of space exploration will be supported by a number of different resources. The public and NASA have realized that future missions, both manned and unmanned, will need to access resources from private sources and international partners, in addition to the traditional government channels.

⁶⁸ [rt.com](https://www.rt.com/news/244797-russia-us-new-space-station/) news. Russia & UW agree to build new space station after ISS, work on joint Mars project. 28 Mar 2015. [cited 2016 Jan 18]. Available from: <https://www.rt.com/news/244797-russia-us-new-space-station/>

⁶⁹ Kremer, Ken. Boeing and SpaceX win NASA's 'space taxi' contracts for space station flights. 17 Sep 2014. [cited 2016 Feb 25]. Available from: <http://www.universetoday.com/114247/boeing-and-spacex-win-nasas-space-taxi-contracts-for-space-station-flights/>

The US military has always been interested and involved in the progress and outcomes of NASA's missions. It is driven by its own goals, however. If another agency is researching and experimenting in areas that aid national defense and security, an attempt is made to coordinate efforts. Military exploitation of scientific discoveries is not a new notion. The twentieth century discovery of nuclear fission by scientists was quickly redirected to the development of a deadly nuclear bomb. The world's pivotal first achievements in space were prompted by the military and political motives of two nations. Today, outer space remains a potential theater of war to not only secure but also take advantage of.



Who Controls Space and How

“There was never a territory in human history that someone didn’t think they could own or make money out of. And that goes for outer space as well...”

–David Barnett, 2015¹

Introduction

The Earth’s first artificial satellite, Sputnik 1, was launched by the Soviet Union on October 4, 1957. It changed the world forever. At that moment, United States space policy and goals were completely refocused on the race to the Moon. During this time, there was an obvious need to determine the legal status of objects in outer space. Perhaps outer space could be considered an extension of governed airspace from Earth’s surface up to orbit. If this were the case, the Soviet Union’s launch of Sputnik would have been seen as a violation of international law. The satellite passed over many countries, including the United States. President Eisenhower, knowing that the US would be interested in having its own spacecraft operating over Soviet territory, accepted that the rules of outer space would be different from controlled airspace and aircraft.²

¹Unoosa.org. [Internet]. c2017. United Nations Office of Outer Space Affairs; [cited 2017 August 16]. Available from: <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html>

²Kleiman, Matthew J. [Internet]. American Bar Association. c2017. Space law 101: an introduction to space law. [cited 2017 Sep 07]. Available from: https://www.americanbar.org/groups/young_lawyers/publications/the_101_201_practice_series/space_law_101_an_introduction_to_space_law.html

When Neil Armstrong and Buzz Aldrin planted the American flag on the Moon, they were symbolizing the end of the Space Race, with a clear victor. They were *not* claiming direct ownership of the celestial body. The Outer Space Treaty 2 years earlier had already made it clear that outer space “is not subject to national appropriation by claim of sovereignty.”³ More than 50 years later, this treaty is becoming a legal obstacle to an exciting era of commercial enterprise—space resource mining.

Space law defines the international and national laws and customs that administer activities in outer space. For a time following the Space Race, outer space operations were primarily being conducted by government agencies. Now, however, private companies are planning and executing missions to explore outer space and access resources. Space law will face many new challenges. This chapter focuses on the specifics of outer space law and will address the issues that the private companies and government organizations will need to address in the next decade and beyond.

The History of Space Law

The Earth’s atmosphere transitions to outer space gradually, as illustrated in Fig. 2.1. Scientists have not defined a precise location where outer space begins, although there are defined atmospheric layers, each indicating a thinner atmosphere along with other distinguishing characteristics. Astronauts or cosmonauts are the only humans to have journeyed beyond the thermosphere, the upper atmosphere layer that extends from about 56 miles to between 311 and 621 miles above our planet. Close to the thermosphere border at approximately 50 miles of altitude, aerodynamic control surfaces are not effective, and rockets are required to steer a vehicle. Orbiting spacecraft, such as low Earth orbit satellites and previously the Space Shuttle, operate in the thermosphere. The ionosphere overlaps the mesosphere and thermosphere atmospheric layers and is dynamic based on solar conditions. The abundance of electrons, ionized atoms, and molecules makes this region an important component of radio communications.

The North American hypersonic jet, the X-15, and its civilian pilots flew to heights of close to 67 miles in 1963, a record that was not broken until the experimental aircraft SpaceShipOne flew to nearly 70 miles many decades later in 2004. For record keeping and awarding astronaut wings, the Kármán Line,⁴ located

³Liechty, David. [Internet]. c2017. The Solari Report with Catherine Austin Fitt; Solari Special Report: Issues and framework of United States law concerning outer space.; Oct 30, 2015 [cited 2017 August 28]. Available from: <https://solari.com/blog/solari-special-report-issues-and-framework-of-united-states-law-concerning-outer-space/>

⁴[IOP] Institute of Physics c2014. London, England [Internet]. [cited 2017 August 3]. Available from: <http://www.iop.org/resources/topic/archive/space/>

about 62 miles above Earth's surface, is roughly identified as the outer space border. At this altitude, a spacecraft begins to completely escape Earth's gravity. More technically, at this point, the velocity required to maintain orbital altitude is equal to the escape velocity, and the spacecraft has achieved the speed to go beyond Earth and enter space. The atmosphere doesn't actually stop at the Kármán Line but rather continues on, gradually tapering off over thousands of miles.

The final layer of the atmosphere, the exosphere, continues at least until 6700 miles beyond the surface of our planet (see Fig. 6.1).⁵ Beyond the exosphere, the moon still lies over 200,000 miles away. Almost all of outer space is still left to be explored. Humans have only traveled to the Moon, where Neil Armstrong left a plaque declaring that the crew intended to "come in peace for all mankind." Beyond the Moon are billions of other celestial objects, including stars, planets and their moons, and asteroids.

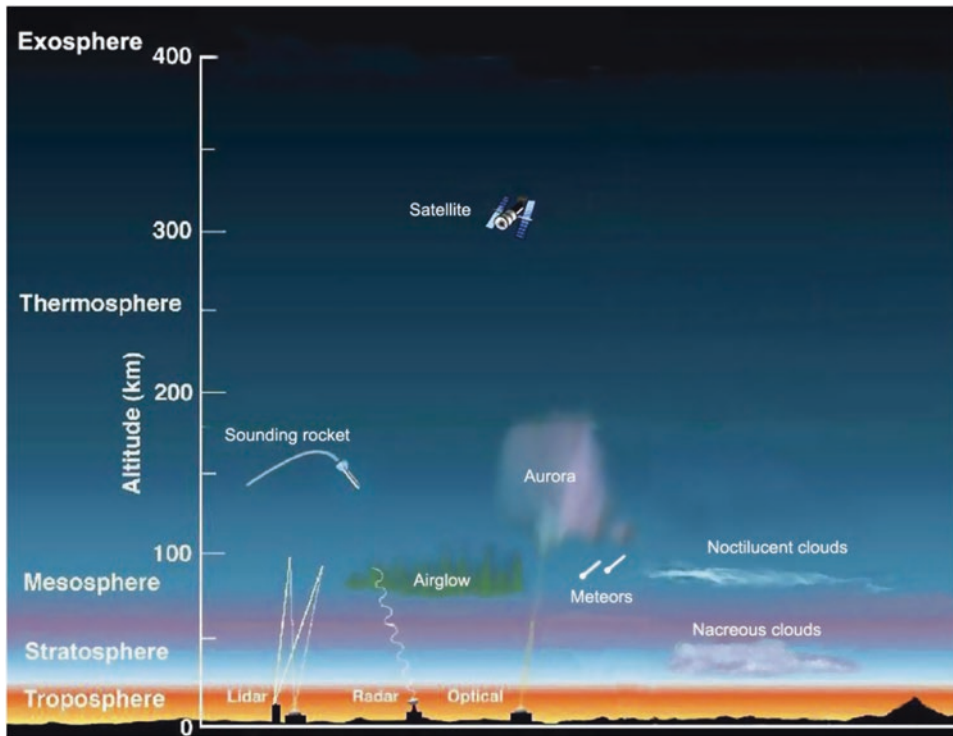


Fig. 6.1. Levels of the Earth's atmosphere. Image Credit: NASA/Goddard

⁵NASA.gov. [Internet]. c2015. Earth's atmospheric layers; [cited 2017 August 3]. Available from: https://www.nasa.gov/mission_pages/sunearth/science/atmosphere-layers2.html

The huge expanse of outer space is an area without defined boundaries, creating questions about who controls the space directly above Earth, the orbiting spacecraft, as well as the other celestial bodies. The issue of who owns what has been discussed by governing bodies since the mid-1950s. In 1958, a year after the Sputnik launch, the United Nations General Assembly created a Committee on the Peaceful Uses of Outer Space (COPUOUS). In 1960, the International Institute of Space Law was created as a nongovernment entity to promote international cooperation in making space law. Topics developed in space law include property rights, weapons and weapon platforms in space, the militarization of space, space debris, and other related matters. In 1967, the United Nations approved an agreement mentioned numerous times before, called the Outer Space Treaty (see Appendix A for a complete text of the treaty). The document's actual title is the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies."⁶ The treaty was presented by the United States, the Soviet Union, and the United Kingdom for international signatures.⁷ As of its 50th anniversary in January 2017, 104 nations are signed parties to the agreement. The treaty sets the ground rules for ensuring the peaceful exploration of space and how nations should interact with each other's property in Earth orbit and beyond.⁸

It is interesting that the US and the Soviet Union initiated this treaty in the midst of the Cold War and the Space Race. They were both concerned about how outer space was going to be divided up in future endeavors, including through colonization efforts. Dr. Jill Stuart, who heads space policy at the London School of Economics, stated at the 50th year anniversary of the treaty signing: "Why bother going to do that? Why not just leave it lawless? Both governments felt that they couldn't control outer space, but it was in their interests to lock the other side into a legal agreement in case the other party found a way to do so."⁹

The Outer Space Treaty was created when space travel was just starting, addressing issues that could only be foreseen as space technology progressed. It is somewhat general and flexible in its language, and so parts of it are up for

⁶Grush, Loren. [Internet]. [Theverge.com](https://www.theverge.com); c2017. How an international treaty signed 50 years ago became the backbone for space law; Jan 27, 2017 [cited 2017 Aug 5]; Available from: <https://www.theverge.com/2017/1/27/14398492/outer-space-treaty-50-anniversary-exploration-guidelines>

⁷Howell, Elizabeth. [Internet]. [Space.com](http://www.space.com); c2016. Who owns the Moon? | Space law and outer space treaties; July 15, 2016 [cited 2017 Aug 4]; Available from: <http://www.space.com/33440-space-law.html>

⁸Johnson, Christopher D. [Internet]. [Thespacereview.com](http://www.thespacereview.com); c2017. The outer space treaty at 50; Jan 23, 2017 [cited 2017 Aug 5]; Available from: <http://www.thespacereview.com/article/3155/1>

⁹Barnett, David. Who owns outer space? And what happens when corporations want to extract resources from asteroids or planets? Independent News. 08 Sep 2015. [Internet]; [cited 2017 July 26]. Available from: <http://www.independent.co.uk/news/world/who-owns-outer-space-and-what-happens-when-corporations-want-to-extract-resources-from-asteroids-or-10492126.html>

interpretation or simply don't address certain aspects of space exploration and future colonization. Nevertheless, it stands as the first space agreement and remains the foundation for international space law. Such United Nations treaties are nonbinding, but other nations can put international pressure on a member party who violates its principles.

In the period when the Outer Space Treaty was being created, there were two separate ways of looking at outer space. The one favored by the US followed the law of the high seas, where watercraft are registered at a country of origin, but the oceans themselves are international and unrestricted. The USSR favored the air-space argument—that whatever space is above your country belongs to you, even heading out to infinity. The Soviet Union was more suspicious of satellites flying over its territory in what could be spying and surveillance activities. Nonetheless, the model of the high seas was adopted, in part because Russia's Sputnik, when launched in 1957, crossed other many countries' airspaces when it orbited over the Earth's surface.¹⁰

According to the United Nations Office for Outer Space Affairs:

The Outer Space Treaty provides the basic framework on international space law, including the following principles:

- The exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all mankind;
- Outer space shall be free for exploration and use by all States;
- Outer space is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means;
- States shall not place nuclear weapons or other weapons of mass destruction in orbit or on celestial bodies or station them in outer space in any other manner;
- The Moon and other celestial bodies shall be used exclusively for peaceful purposes;
- Astronauts shall be regarded as the envoys of mankind;
- States shall be responsible for national space activities whether carried out by governmental or non-governmental entities;
- States shall be liable for damage caused by their space objects; and
- States shall avoid harmful contamination of space and celestial bodies.¹¹

¹⁰ Barnett, David. Who owns outer space? And what happens when corporations want to extract resources from asteroids or planets? Independent News. 08 Sep 2015. [Internet]; [cited 2017 July 26]. Available from: <http://www.independent.co.uk/news/world/who-owns-outer-space-and-what-happens-when-corporations-want-to-extract-resources-from-asteroids-or-10492126.html>

¹¹ [Unoosa.org](http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/intro-outerspacetreaty.html). [Internet]. c2017. United Nations Office of Outer Space Affairs; [cited 2017 August 16]. Available from: <http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/intro-outerspacetreaty.html>

These principles focus on outer space as a territory to be explored and enjoyed by everyone. Emphasis is placed on peaceful applications and the banning of weapons in space. In addition, participating nations are responsible for any damage or contamination caused by their own space objects. Causation and damage are difficult to determine and to enforce. The language in the treaty is somewhat vague, probably a deliberate move. It was unknown what would lie ahead in terms of questions of ownership and national priorities.

Four other agreements were put into place in the 1960s and 1970s to elaborate on specific parts of the Outer Space Treaty. These agreements are described below and summarized in Table 6.1.

Table 6.1. A summary of outer space treaties and agreements

Treaty	Year	Main points
Outer Space Treaty	1967	Outer space is destined to be used for the benefit of all countries and remain weapon-free.
The Rescue Agreement	1968	All reasonable steps should be taken to assist and/or rescue astronauts in distress and help to return them to their launch location.
The Liability Convention	1972	A launching state (spacecraft owner) is liable to pay compensation for damage caused by its space object.
The Registration Convention	1976	A system to identify and register launched space objects, proving ownership data to determine damage liability.
United Nations Moon Agreement	1984	A restatement of the Outer Space Treaty in addition to precluding the Moon as a source of international conflict.

The Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (the “Rescue Agreement”) (December, 1968) requires that all engaged countries, “prompted by the sentiments of humanity,” use all possible practical methods to rescue or assist astronauts in danger and eventually aid them in returning back to their launch location. The Agreement also specifies that nations should help to recover space objects that land back on Earth outside of the launching nation’s territory.¹²

The Convention on International Liability for Damage Caused by Space Objects (the “Liability Convention”) (1972) outlines the liabilities and required actions if a spacecraft causes harm or loss of human life. Its first article says, “A launching state shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft flight.”¹³ Thus, if a damaged

¹²Dembling, Paul G., Arons, Daniel M. 1968. The treaty on rescue and return of astronauts and space objects. *William & Mary Law Review*. 9(3): 630–663.

¹³Burke, Joseph A. 1984. Convention on International Liability for Damage Caused by Space Objects: definition and determination of damages after the Cosmos 954 incident. *Fordham International Law Journal*. 8(2): 255–285.

spacecraft or space station reenters the atmosphere or if two satellites crash together, the nation of ownership is held responsible. The convention also states that if two or more parties jointly launch a spacecraft, they can each be held independently liable for the full damage cost, regardless of a party's share.¹⁴

After the crash of the Soviet nuclear-powered surveillance satellite Cosmos 954 in the Northwest Territories of Canada on January 24, 1978, questions arose as to whether Cosmos 954 had caused "damage" as defined in Article 1 of the Liability Convention. Both nations were parties to the agreement. The debris from the Cosmos reactor was radioactive, and the crash site spread a large expanse of radioactivity. There was no direct damage to property or physical injury, but nevertheless, Canada took precautionary measures to prevent hazards to public health from the satellite's radioactive emissions. Radioactive pieces of the satellite were located and removed by decontamination teams. Canada tried to recover the costs from the Soviet Union for cleaning up the satellite debris. To date, the cleanup request following the Cosmos incident is the only claim that has ever been made under the Convention.

The crash of Cosmos 954 introduced international space policy issues. Soon after the satellite's crash, the United States requested that satellites launched into orbit around the Earth be forbidden from containing radioactive material. Canada and other countries in Europe followed up with similar requests. In late 1978, the United Nations sanctioned the Committee on the Peaceful Uses of Outer Space to set up a task force to study nuclear-powered satellites.¹⁵

The Convention on Registration of Objects Launched into Outer Space (the United Nations "Registration Convention") (1976) created a system to register space objects in order to identify launched objects. This information provides ownership data so that damage liability can be more easily proved. Participants of the convention are expected to provide categorizing information to the United Nations, including: the name of launching state or states; an appropriate designator of the space object or its registration number; date and location of launch; the general function of the spacecraft; and basic orbital parameters. Importantly, the United Nations registry assists in the avoidance of space debris.¹⁶ The United States Strategic Command offers real-time updates to NASA if space debris is endangering a spacecraft or the International Space Station (see Chap. 4 on space debris).

¹⁴Swaminathan, S. The applicability of space law principles to basic space science: an update. 2005. Seminars of the United Nations programme on space applications. Selected papers from activities held in 2004. United Nations, New York. p. 117.

¹⁵Hc-sc.gc.ca. [Internet]. c2008. Health Canada, Health Concerns; [cited 2017 August 27]. Available from: http://www.hc-sc.gc.ca/hc-ps/ed-ud/fedplan/cosmos_954-eng.php

¹⁶Liechty, David. [Internet]. c2017. The Solari Report with Catherine Austin Fitt; Solari Special Report: Issues and framework of United States law concerning outer space.; Oct 30, 2015 [cited 2017 August 28]. Available from: <https://solari.com/blog/solari-special-report-issues-and-framework-of-united-states-law-concerning-outer-space/>

The United Nations Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (United Nations “Moon Agreement”) (1984) gives more detail about property rights and use of the Moon and other celestial bodies in the Solar System (except for objects that naturally enter the Earth from these bodies, such as meteorites). The United States has not signed this agreement, nor has Russia, China, Japan, or most of the countries involved in the European Space Agency. The only signing nations are minor players in space exploration. It has been adopted by the United Nations General Assembly, indicating the future direction of international law concerning activities on celestial bodies. As in the Outer Space Treaty, the agreement essentially restates that the Moon and other celestial bodies should be used for the benefit of all states, and that their exploration should be carried out in a peaceful manner. It also states that the Moon should not be a source of international conflict. Because so few nations have agreed to the contract at this point, it is not relevant to current space activities but could be a factor in the future when increased missions to the Moon and Mars, along with space settlements, become a reality.¹⁷

The United States constructed additional guidelines for its own commercial spaceflight with the following acts. The first was the US Commercial Space Launch Act (1984), which designated the Department of Transportation as the federal agency responsible for regulating commercial space launch activities. More recently, the US Commercial Space Launch Competitiveness Act (2015) made a number of modifications to US commercial space policy, including awarding property rights to US companies that mine resources from asteroids. Its objective was to incentivize private aerospace competitiveness and entrepreneurship.¹⁸

In addition to these space treaties and acts, COPUOUS created five sets of principles (legal, broadcasting, remote sensing, nuclear power sources, and benefits) in support of these agreements, which elaborated on specific technologies developed:

1. **Broadcasting Principles** (1982) address television broadcast signals, focusing on noninterference with signals from other countries. The foundational values are to share information for the exchange of knowledge and the promotion of educational and social development.
2. **Remote Sensing Principles** (1986) concern the use of electromagnetic waves to gather data on Earth’s natural resources. Remote-sensing activities are expected to be carried out for the benefit of all countries and in the spirit of international cooperation.

¹⁷ Howell, Elizabeth. [Internet]. [Space.com](https://www.space.com/33440-space-law.html); c2016. Who owns the Moon? | Space law and outer space treaties; July 15, 2016 [cited 2017 Aug 4]; Available from: <https://www.space.com/33440-space-law.html>

¹⁸ [Congress.gov](https://www.congress.gov/bill/114th-congress/house-bill/2262/text). [Internet]. c2018. H.R.2262—U.S. commercial space launch competitiveness act; [cited 2018 May 24]. Available from: <https://www.congress.gov/bill/114th-congress/house-bill/2262/text>

3. **Nuclear Power Sources Principles** (1992) address concerns over the risks posed by launching nuclear powered spacecraft. It is common for spacecraft exploring the outer Solar System to use nuclear power sources for energy, and those objects pose a risk for both launch and entry. The principles protect humans and other species from radiation in case of an accidental mishap or crash.
4. **The Benefits Declaration** (1996) states that space exploration should be conducted for the benefit of all states. It further defines the contents of the Outer Space Treaty. It originated 2 years before the International Space Station launched its first two modules into space.¹⁹

Major questions exist as we move towards an increased number of spacefaring nations and see the rise of commercial enterprises with planned missions to ferry passengers, gather data, mine materials, and deploy instrumentation into outer space. The various issues of concern are addressed below.

Commercial Human Spaceflight

Soon, humans will have the opportunity to travel routinely into outer space on spacecraft built and operated by private companies. SpaceX's Dragon (illustrated in Fig. 6.2) and its competitor, Boeing's CST-100 Starliner, will be transporting astronauts to the International Space Station after vehicle certification is completed by NASA.²⁰ The first spaceflights will be suborbital—that is, the spacecraft is in outer space for only a few minutes, launching from and returning to the same location. Sir Richard Branson, the founder of Virgin Galactic, has said that the company is readying to launch passengers into suborbital space in the 2018–2019 timeframe. In addition, private companies are expected to take passengers on orbital spaceflights to privately operated space habitats in the not too distant future.²¹ Elon Musk, founder of SpaceX, has also announced plans for a bold new mission where two passengers will fly in a full orbit of the Moon. Without the benefit of broader government support, this will be the first entirely private passenger flight of this type ever attempted.²²

¹⁹ Howell, Elizabeth. [Internet]. Space.com; c2016. Who owns the Moon? | Space law and outer space treaties; July 15, 2016 [cited 2017 Aug 4]; Available from: <https://www.space.com/33440-space-law.html>

²⁰ Bennett, Jay. [Internet]. popularmechanics.com; c2017. After delays, SpaceX and Boeing aim to launch astronauts next year; July 24, 2017 [cited 2017 Sep 29]; Available from: <http://www.popularmechanics.com/space/a27453/spacex-boeing-launch-astronauts-next-year/>

²¹ Quinn, James. [Internet]. telegraph.co.uk; c2017. Sir Richard Branson vows to have Virgin Galactic passengers in space by the end of 2018; Apr 2, 2017 [cited 2017 Sep 29]; Available from: <http://www.telegraph.co.uk/business/2017/04/02/sir-richard-branson-vows-have-virgin-galactic-passengers-space/>

²² <https://money.cnn.com/2018/06/07/technology/future/spacex-falcon-heavy-moon-tourists/index.html>



Fig. 6.2. SpaceX Dragon commercial cargo craft on approach to ISS. Image Credit: NASA

Commercial human spaceflight will need to address many complex legal issues. In the same way that aircraft became licensed and monitored in the US by the Federal Aviation Administration (FAA), licensing and safety criteria for private spacecraft are being seriously discussed as the industry matures. There is concern over a developing gap in regulations. The United States commercial space activities may not be in accordance with Article VI of the Outer Space Treaty, which requires a state to “authorize and continually supervise” the spacecraft and the flights by its own nationals.

The Commercial Space Launch Competitiveness Act in 2015 took steps to fill this gap. New bills are now being proposed to give the FAA the authority to license space missions. The FAA is interested in regulating space activities, including Moon Express’s planned mission to return to the Moon to mine valuable resources. Liability concerns, insurance requirements, and questions about informed consent will also need to be addressed by space companies and the courts.²³

²³ Sundahl, M. J. Regulating non-traditional space activities in the United States in the wake of the Commercial Space Launch Competitiveness Act. *Air & Space Law*, 42(1); 29–42.

Space Debris

More than 500,000 pieces of space debris are being tracked while they orbit the Earth—remnants from over 50 years of space travel. The objects travel at extremely high velocities (up to 17,500 mph), fast enough for even a small fragment of orbital debris to severely damage a satellite or a spacecraft. The increasing population of space debris escalates the potential danger to all space vehicles, including the International Space Station. An illustration of debris in low Earth orbit is shown in Fig. 6.3. The topic of space debris as it relates to aggressive activities in outer space territory was discussed in detail in Chap. 4. Future space travel could be restricted by such obstacles. Currently, there are no legal ramifications for those who create more debris by abandoning unused spacecraft, those who don't monitor for possible interference or collisions with other objects, or those who do not have concrete plans for retrieving or deorbiting aging spacecraft. If future tensions between nations lead to the weaponization of outer space, the proliferation of space debris would further limit access to low Earth orbit.

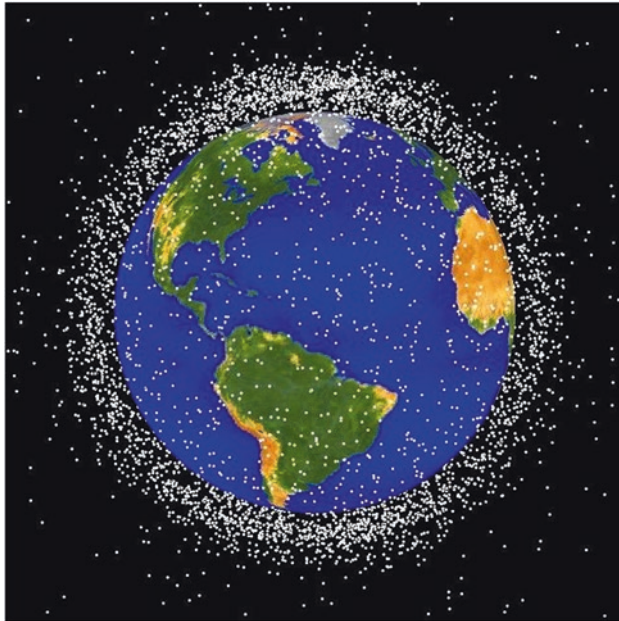


Fig. 6.3. Image of debris in low Earth orbit. Image Credit: NASA

Mining Rights

In 2013, scientists in Scotland discovered several asteroids orbiting Earth that were close enough to be mined, or blasted into an accessible orbit and then mined, for industrial and precious metals.²⁴ Geologists believe that asteroids hold iron ore, nickel, and precious metals at much higher concentrations than those found on Earth. Precious metals are more difficult to find than other types of metals. They are naturally occurring metals with a higher luster than base metals and are very pliable without losing toughness. These characteristics distinguish them from regular base metals and allow them to fetch higher prices than base metals. The most well-known precious metals include gold, silver, platinum, and palladium.²⁵

Many scientists believe that many of the metals currently being used here on Earth are being rapidly depleted. They claim that unless there are new technological advances, metals like zinc and gold are expected to run out in 100 years, making asteroid mining a necessity. So far, there are at least two asteroid mining companies: Planetary Resources, a startup backed by director and ocean explorer James Cameron and Google billionaires Peter Diamandis and Eric Anderson, and Deep Space Industries (along with NASA). Both are looking into the feasibility of outer space mining. If precious metals are plentiful in space, and if a company can access it, mining could add trillions of dollars to the global economy, according to Planetary Resources' own estimates.²⁶ There are millions of asteroids in the main asteroid belt between Mars and Jupiter, some as large as small moons. It is estimated that there are a million separate near-Earth asteroids that have drifted away from the asteroid belt and took on stable solar orbits much closer to us. Anderson notes that there are 8931 close objects that have been documented and mapped (see illustration in Fig. 6.4).²⁷ California-based Deep Space Industries and Washington State-based Planetary Resources are currently working toward extracting resources from asteroids in order to supply essentials out in deep space. These include water, rocket fuel, and building materials, which are heavy and prohibitively expensive to transport from Earth. Both firms say they plan to launch spacecraft to prospect asteroids by late 2020, with mining taking place soon thereafter.²⁸

²⁴ Jamasmie, Cecilia. [Internet]. [mining.com](http://www.mining.com); c2013. Astronomers identify 12 asteroids close enough for mining; Aug 12, 2013 [cited 2017 Sept 27]; Available from: <http://www.mining.com/astronomers-identify-12-asteroids-close-enough-for-mining-29724/>

²⁵ Sciencestruck. [Internet]. sciencestruck.com. c2017. A comprehensive list of precious metals, their properties, and uses. [cited 2017 Oct 1]. Available from: <https://sciencestruck.com/list-of-precious-metals>

²⁶ Jamasmie, Cecilia. [Internet]. [mining.com](http://www.mining.com); c2013. Astronomers identify 12 asteroids close enough for mining; Aug 12, 2013 [cited 2017 Sept 27]; Available from: <http://www.mining.com/astronomers-identify-12-asteroids-close-enough-for-mining-29724/>

²⁷ Poeter, D. James Cameron, Google duo back asteroid-mining venture. PC Magazine. April 2012; 1.

²⁸ Slezak, M. Space mining: the next gold rush? New Scientist. March 2, 2013; 217(2906), 8–10.

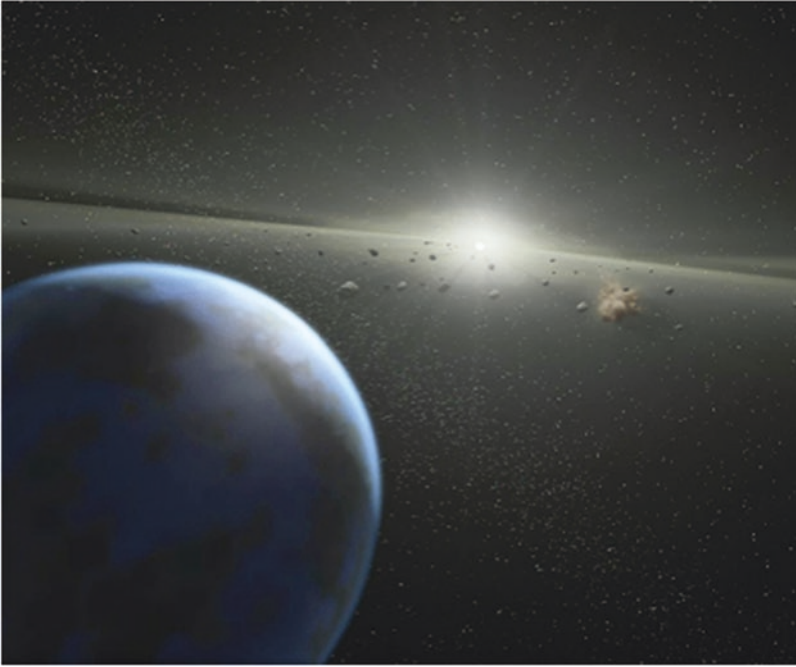


Fig. 6.4. Astronomers have identified 12 asteroids close enough to Earth to mine precious metals. 8931 close objects have been mapped. Image Credit: NASA

US companies such as Planetary Resources, Deep Space Industries, Shackleton Energy Resources, and Moon Express are all focused on surveying and developing outer space resources for commercial purposes. The focus of space mining has changed somewhat, from extracting precious metals to extracting water. The easiest resource to access is water, says Deep Space Industries chief scientist John Lewis. The liquid can be converted electrically into hydrogen and oxygen for fuel. The mass of the asteroids consists of as much as 10% water. It is embedded in minerals and can be baked out in a solar oven. Modified terrestrial mining techniques could be used to harvest iron from asteroids as well as precious metals.²⁹

Interest in space mining for profit has increased, both in the United States and other countries—even in the tiny country of Luxembourg (a surprising hotbed for space-related pursuits and discussions). In November 2015, President Obama

²⁹ Dunietz, Jesse. [Internet]. [scientificamerican.com](https://www.scientificamerican.com/article/floating-treasure-space-law-needs-to-catch-up-with-asteroid-mining/); Floating treasure: space law needs to catch up with asteroid mining. 28 Aug 2017. [cited 2017 Sep 5]. Available from: <https://www.scientificamerican.com/article/floating-treasure-space-law-needs-to-catch-up-with-asteroid-mining/>

passed the US Commercial Space Launch Competitiveness Act, beginning a new phase of the commercial space industry. The Act's long title claims "To facilitate a pro-growth environment for the developing commercial space industry by encouraging private sector investment and creating more stable and predictable regulatory conditions, and for other purposes." The Space Act updates parts of the Commercial Space Launch Act of 1984, which helped expedite the commercialization of space and space technology. It addressed the new reality of commercial space, which mixes both government and private enterprise in human spaceflight. It also cleared the way for private companies to mine asteroids and extract resources from celestial bodies for economic gain. The bill, sponsored by House Majority Leader Kevin McCarthy (R-Calif.), declares that a "United States citizen engaged in commercial recovery of an asteroid resource or a space resource under this chapter shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell the asteroid resource or space resource obtained in accordance with applicable law, including the international obligations of the United States."³⁰

There are several legal issues to overcome in order to claim ownership of space assets and use them for tactical or economic advantage. The Outer Space Treaty of 1967 has been seen as a major impediment to the commercial development of space assets. In the 1960s, mining had not been envisioned as a profitable or even possible venture. The US Commercial Space Launch Competitiveness Act of 2015 includes somewhat of a loophole for the Outer Space Treaty, which declares that no "celestial body" shall be subject to "national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." The more recent Space Act does not allege sovereignty rights. Instead, it defines how US law would handle property claims by any company, domestic or foreign.³¹ The law creates a legal framework for companies who plan to develop new space technologies, generate rocket fuel, extract resources, and more. The legalities and details of mining rights and their consistency with the Outer Space Treaty are still being debated. Mining resources from celestial bodies can be looked at as similar to the status of high seas, where no state can colonize or own the Pacific Ocean, yet anyone can harvest the fish contained within. Other countries agree with this interpretation and are interested in exploiting outer space for profit, from one of the largest (China) to the smallest (Luxembourg). Opponents of this viewpoint say that if outer space belongs to everyone, so do its resources.

³⁰ H.R.2262, [Internet] 114th Congress (2015–2016), introduced by Rep. Kevin McCarthy. [cited 2017 Aug 31] Available from: <https://www.congress.gov/114/bills/hr2262/BILLS-114hr2262enr.pdf>

³¹ Mangu-Ward, K. Profits in space. Reason. 47(10): 8–9.

Even if a company can sidestep current legal obstacles, it is not certain that space mining would be as lucrative as those at Planetary Resources envisions. If such companies were to bring back stockpiles of such resources, the influx could disrupt the current precious metal industry and economy.

Figure 6.5 illustrates the NASA's OSIRIS-REx spacecraft travelling to the water-rich asteroid Bennu, a mission to return to Earth a small sample of rock for scientific study. At the time of writing, the spacecraft is on track to reach Bennu in 2018 and return a sample to Earth by 2023. Another NASA mission (illustrated in Fig. 6.6) will travel in 2022 to a giant metal asteroid named Psyche, which is orbiting the Sun between Mars and Jupiter. What makes Psyche unique is that it appears to be composed of nickel-iron core of an early planet, one of our Solar System building blocks. The mission will help scientists understand how planets and other celestial bodies separated into layers early in history.³²

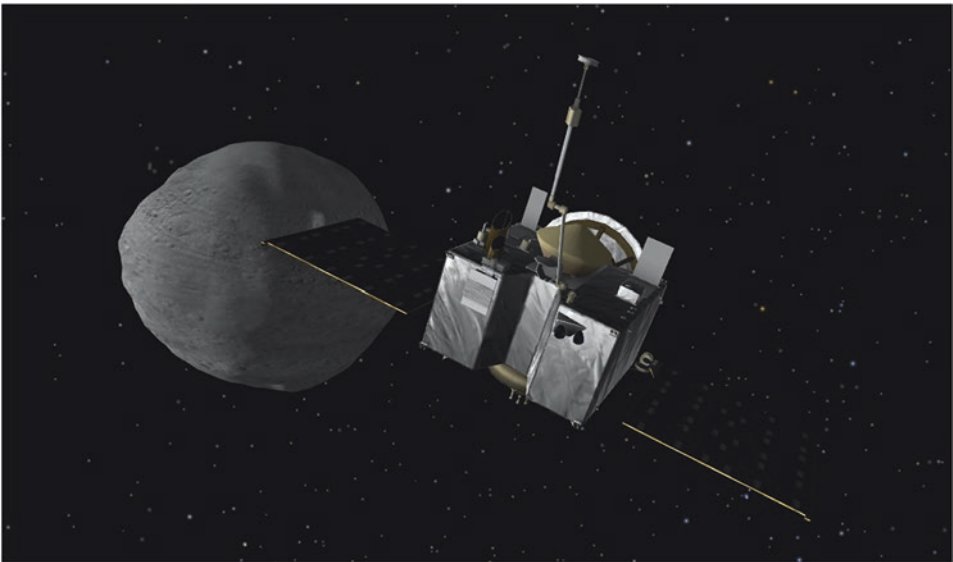


Fig. 6.5. NASA's OSIRIS-REx spacecraft preparing to extract a rock sample from the near-Earth asteroid called Bennu. Image Credit: *NASA/Goddard*

³² Dunietz, Jesse. [Internet]. [scientificamerican.com](https://www.scientificamerican.com/article/floating-treasure-space-law-needs-to-catch-up-with-asteroid-mining/); Floating treasure: space law needs to catch up with asteroid mining. 28 Aug 2017. [cited 2017 Sep 5]. Available from: <https://www.scientificamerican.com/article/floating-treasure-space-law-needs-to-catch-up-with-asteroid-mining/>



Fig. 6.6. Artistic rendition of the Psyche spacecraft. Image Credit: *NASA/JPL*

Luxembourg has been studying the mining of asteroids as a commercial enterprise since 2013 and has been interested in investing in private companies and research and development programs. The nation's Minister for the Economy said that the goal is to "open access to a wealth of previously unexplored mineral resources on lifeless rocks [hurtling] through space, without damaging natural habitats." Chris Lewicki, chief executive of Planetary Resources, said the company would work with Luxembourg, as would Deep Space Industries.³³

An amended US bill, The Space Resource Exploration and Utilization (SREU) Act of 2015, safeguards the rights of mining companies that are willing to invest sizeable finances in future space exploitation. For example, a mining company would have the right to develop the Martian resources and still be protected under US Federal Law if it establishes a base on Mars.³⁴ A manned mission to Mars is the most exciting near-term mission. Some of the talk is therefore focused on the legality of utilizing and extracting its resources.

³³ Wall, R. 04 Feb 2016. Luxembourg to back commercial asteroid-mining ventures. *Wall Street Journal*—Online Edition. p. 1. [cited 2017 Sep 5]. Available from Academic Search Complete.

³⁴ Dodge, M. Fall 2016. The U.S. commercial space launch competitiveness act of 2015: moving U.S. space activities forward. *Air and Space Lawyer*, 29(3), 4–8.

The SREU Act defines the range of resources subject to extraction and utilization. For example, an “asteroid resource” is defined as “a space resource found on or within a single asteroid.” “Space resource” is then defined as any nonbiological resource found *in situ*, or in its original place in outer space (which may not be the asteroid itself). Both water and minerals are included under the umbrella of space resources. However, the language prohibits the appropriation of celestial bodies, as required by the Outer Space Treaty. Additionally, the US has no intention to claim, or to allow private companies to claim, any lifeforms discovered on other celestial bodies. The SREU Act promotes US commercial exploration and recovery in space. Congress directs the President, along with “appropriate” agencies, to encourage the development of the space resource industry and remove barriers to newcomers. It specifically discourages any governmental red tape that would impede the successful growth of an “economically viable, safe, and stable” space resource industry. The law further instructs the President to expedite the commercial exploration and recovery of space resources. Taken together, these provisions represent a stronger government role in partnering with and supporting private industry.³⁵

SpaceX, a prominent US space company led by Elon Musk, has strong ties to NASA, holding multiple contracts to deliver supplies and eventually astronauts to the International Space Station. The company’s plans to set up a human settlement on Mars have been delayed, primarily due to issues with rocket development. SpaceX is projecting the first human mission to Mars for 2022. Prior to this timeframe, several non-manned missions will be used to demonstrate its advanced technologies. SpaceX’s Dragon capsule was scheduled to conduct a powered, soft landing on the Martian surface. The capsule itself would have been launched by another new piece of technology, SpaceX’s Falcon Heavy rocket. The Red Dragon project was halted in 2017. The company is now working on a Big Falcon Rocket (BFR), which will use resources redirected from SpaceX’s other ventures to complete a 2022 mission to Mars.

Both SpaceX and NASA are planning flights to Mars. Musk has lofty plans to colonize the Red Planet, sending up to a million people on more than 1000 space-ships, a risky activity that would stretch over decades or even lifetimes. Building on its robotic successes, NASA’s goal is to send humans to Mars in the 2030s after a series of increasingly challenging missions. SpaceX and NASA will work collaboratively for at least one launch. NASA will provide SpaceX with technical support, including data transmission from deep space, flight systems and engineering, and mission design and navigation. In exchange, NASA is interested in the entry, descent, and landing data from the capsule.³⁶ Figure 6.7 is an artist’s conception of two astronauts working to extract an intact core sample from the Martian surface.

³⁵ Dodge, M. Fall 2016. The U.S. commercial space launch competitiveness act of 2015: moving U.S. space activities forward. *Air and Space Lawyer*, 29(3), 4–8.

³⁶ NASA. [Internet]. [nasa.gov](https://www.nasa.gov); c2017. The journey to mars overview. Last updated Aug 3, 2017. [cited 2017 Sep 04]; Available from: <https://www.nasa.gov/content/journey-to-mars-overview>

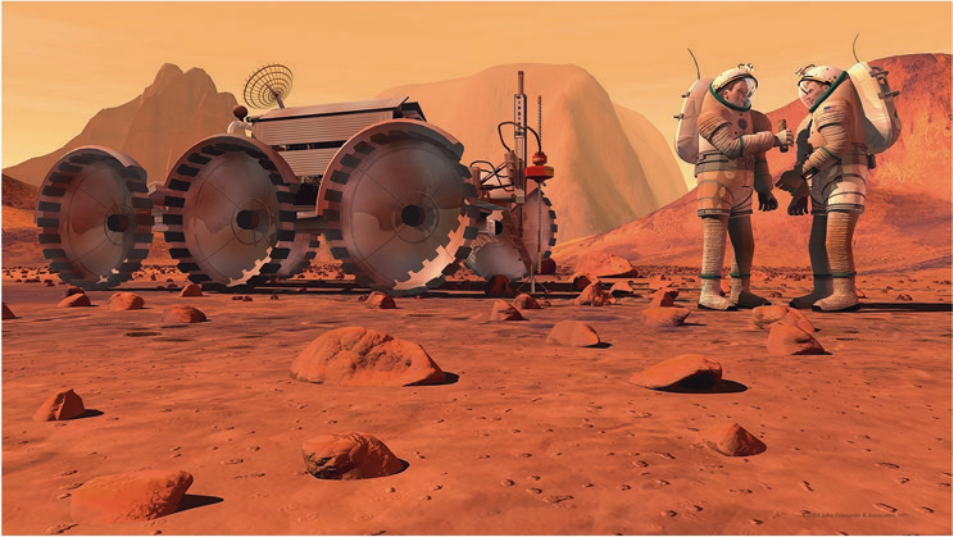


Fig. 6.7. Martian surface drilling and sample collection. Image Credit: NASA

Another well-known, newer space company also recently awarded NASA contracts is Blue Origin, created by Amazon's founder, Jeff Bezos. Blue Origin has unveiled plans for a launch vehicle called the New Glenn, with the capability of lifting astronauts to low Earth orbit and beyond. According to a company report sent to NASA officials and President Trump, Blue Origin is interested in developing a lunar spacecraft and lander, and eventually, a delivery service for the Moon.³⁷

The FAA has to clear each launch by a private company in the US. The Outer Space Treaty has generally defined space exploration and colonization. It is not clear how the treaty will affect commercial activities like resource exploitation or settlements on other planets. The FAA is interested in Article VI of the treaty and how it might impact SpaceX's planned mission to Mars. Article VI states that all signees to the treaty "shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities." As mentioned previously, Article VI also says, "The activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty." This verbiage states that the US government itself would bear

³⁷ Masunaga, Samantha. Don't expect a space race between SpaceX and NASA. They need each other. LA Times. 05 March 2017. [Internet]; [cited 2017 Sep 5]. Available from: <http://www.latimes.com/business/la-fi-spacex-nasa-20170301-story.html>

responsibility for the SpaceX Mars mission. The bulk of resource utilization and commercial space exploration will originate in the US, so how the US interprets the treaty commitment will be of international interest.³⁸

The SpaceX mission to Mars will be a test for how the Outer Space Treaty may be challenged or upheld in the near future. More countries and private companies are becoming spacefarers every year. The legality of certain space missions and future human presence back on the Moon and on Mars will be an interesting and high-stakes discussion.

Reflections

As was the case at the start of the Space Race, governments who claim that their activities are peaceful and scientific may still have something to gain militarily. If one nation can project power into space, either via real weapons or via a symbolic statement, it will gain an edge over its rivals. International treaties that seek to monitor such activities are subject to the motives and agendas of participating nations. The Space Treaty of 1967 listed a number of principles describing what nations can and cannot do in space, who owns space, and what can be done on other celestial bodies. So far, no signing nation has had an opportunity to violate the treaty, although the asteroid mining law (Commercial Space Launch Competitiveness Act of 2015) passed by the US Congress comes close. It is a critical step forward in US commercial space, but it is by no means the last one that will be taken.

In addition to property issues, there needs to be a coherent US approach to regulating commercial space that prioritizes safety, minimizes industry regulations, and promotes this growing sector of the economy. This legislative directive should conform with US obligations under Article VI of the Outer Space Treaty, requiring authorization and continued supervision of such activities by the state.³⁹ The new reality of commercial space involves the intermixing of government and private enterprise in human spaceflight.

Boundary disputes and property rights are other areas of possible contention. For example, two separate parties may claim rights to access a certain region of an asteroid. Right now, the Outer Space Treaty says that space and celestial bodies cannot be claimed by other nations, but it is unclear how these requirements apply to private companies. The US Commercial Space Launch Competitiveness Act

³⁸ Gough, Evan. SpaceX calls in the lawyers for 2018 Mars shot. 20 May 2016. [Internet]; [cited 2017 Sep 5]. Available from: <https://www.universetoday.com/129024/spacex-calls-lawyers-2018-mars-shot/>

³⁹ Unoosa.org. [Internet]. c2017. United Nations Office of Outer Space Affairs; [cited 2017 August 16]. Available from: <http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/intro-outerspacetreaty.html>

does not agree to territorial claims, but with nations talking about landing on places such as the Moon and Mars, it is unclear how exploitation and property rights would apply in the case of adjacent colonies. Some suggest that Antarctica, a territory owned by no nation and used mainly for scientific purposes, could be a model to follow, but not everyone agrees.⁴⁰

Ownership even becomes an issue in empty space. Geosynchronous satellites that are positioned roughly 26,000 miles above the equator have the same rotation period as the Earth, allowing them to remain in approximately the same location above Earth for long periods of time without expending large amounts of fuel. This is useful for telecommunications signals and other applications. Such slots are limited and are regulated by the International Telecommunication Union. Nations have in the past tried to exert ownership over this region of space, but these claims have been turned away due to the restrictions detailed in the Outer Space Treaty.

The future will be an interesting mix of government and private enterprise ventures into space. Regulations and supervision of these activities are not completely established under existing space law. Even if a legal framework is properly defined and agreed upon, the question of enforcement and policing of such policies remains largely untested.

⁴⁰ Howell, Elizabeth. [Internet]. [Space.com](https://www.space.com/33440-space-law.html); c2016. Who owns the Moon? | Space law and outer space treaties; July 15, 2016 [cited 2017 Aug 4]; Available from: <https://www.space.com/33440-space-law.html>



The Cold War and Missile Defense

“But it is inconceivable to me that we can go on thinking down the future, not only for ourselves and our lifetime but for other generations, that the great nations of the world will sit here, like people facing themselves across a table, each with a cocked gun, and no one knowing whether someone might tighten their finger on the trigger.”

—President Reagan, 1983¹

Introduction

The Cold War (1945–1991)² was a nontraditional conflict between two conflicting ideologies—communism and democracy. The Soviet bloc countries (USSR) were pitted against the US-led Western powers. Rather than manifesting as a traditional conflict waged through extensive use of weapons, the Cold War was conducted using propaganda, political hostility, and threats. America’s free-market capitalism was used as a powerful positive force against communism, a form of socialism. Most importantly, the two superpowers leading the charge both possessed weapons of mass destruction. Many major crises occurred during the Cold War decades, a few bringing the world to the brink of nuclear war.

¹ Peters, Gerhard and Woolley, John T. The American Presidency Project. 2015. Ronald Reagan: remarks and a question-and-answer session with reporters on domestic and foreign policy issues [Internet]; [cited 2017 June 23]. Available from: <http://www.presidency.ucsb.edu/ws/?pid=41100>

² The Encyclopedia Britannica, Inc. [Internet]. c2017. The Encyclopedia Britannica; [cited 2017 June 22]. Available from: <https://www.britannica.com/event/Cold-War>

In order to defend America and its allies against missiles carrying nuclear warheads (called Intercontinental Ballistic Missiles, or ICBMs), several methods of defense were considered. Space-based lasers and various ways of intercepting and destroying missiles were proposed and studied in the 1980s. Missile defense can be a complex system, involving the detection, tracking, intercepting, and destruction of missiles. Such a system can be ground- or space-based. Both have extreme technological challenges. Decades later, no reliable systems exist to intercept ICBMs. This chapter focuses on post-World War II policies on missile defense through the proposed and partial development of missile and satellite defense through the mid-1990s.

The Concept of Anti-Missile Defense

Missile defense aims to prevent or protect against enemy attacks in the form of weapons delivered on ballistic missiles. Anti-missile systems need to have sophisticated sensor technology in order to detect and acquire targets. Further, space-based sensors, airborne weapons, and ground-based interceptor missiles need to coordinate in order to be used effectively.

When a target is identified and acquired, the system must estimate its speed and trajectory. Once this calculation is made, the system would aim the kill mechanism toward the incoming missile. The kill method could take on a variety of forms: exploding a warhead near it, hitting it directly with a kinetic or blunt-impact warhead, or by using a laser to cause an explosion. Each method has its challenges, advantages, and disadvantages.

Missile interceptors are analogous to the anti-aircraft methods of acquiring and killing a moving enemy target. However, the required distances traveled are much longer and the speeds are much faster, so the sensor resolution and homing technology have to be pinpoint accurate. This process has been referred to as “hitting a bullet with a bullet.”³ Since 1999, the technology for actually intercepting a missile has succeeded approximately 50% of the time, with fewer than 20 overall attempts. A 2016 test of a long-range, ground-based interceptor is shown in Fig. 7.1. The US’s most recent missile defense system (the Ground-based Midcourse Defense) successfully tested its interceptor defense technology in May 2017. The system was able to prove its ability to identify, track, and destroy a target. Of course, in this demonstration, the target was a known object launched for testing and validation purposes. The test did not prove that the system could defend against a real foreign missile attack; it was a small success for a system that the US has spent nearly two decades testing.⁴

³Dowling, B. 27 May 2017. Pentagon orders takeout - Targeting inbound dummy ICBM like ‘hitting a bullet with a bullet’, Boston Herald (MA), p. 8.

⁴Berlinger, Joshua & Callahan, Michael. CNN Politics. 11 Jul 2017. [Internet]. c2017. CNN; [cited 2017 Nov 5]. Available from: <http://www.cnn.com/2017/07/11/politics/us-thaad-missile-defense-test/index.html>



Fig. 7.1. A long-range ground-based interceptor missile launches from Vandenberg Air Force Base, California during a non-intercept flight test on January 29, 2016. Image Credit: *Defense Department*

To be fair, this is an extremely complex and difficult technical problem. Both the incoming missile and the interceptor are traveling about 15,000 mph. The objects have to be lined up to arrive at the same time and at the same location in order to impact or disturb the trajectory of the incoming missile. This type of ground-based interceptor system launches a rocket that then releases a “kill vehicle,” an independent, small device with its own thruster and guidance system that delivers a deadly impact without explosives. The scripted tests were carried out successfully, but any real surprise strike from North Korea or elsewhere will have unknowns, including the source country’s ability to deploy decoys and other countermeasures meant to confuse the targeting systems.⁵ The US can be cautiously optimistic about the program, but there is reason to believe that there would be only limited success in defending US soil in a full attack with multiple warheads. The missile interceptor system has to perform consistently under real-world conditions before we can depend on this method of defense against incoming ballistic missiles. Thus, the testing and development continues (Fig. 7.2).



Fig. 7.2. A ground-based missile interceptor is lowered into its missile silo at Fort Greely, Alaska. Image Credit: www.army.mil

⁵ Barrett, Brian. 30 May 2017. US missile defense still has a long, long way to go. [Internet]. [cited 2017 Nov 7]. Available from: <https://www.wired.com/2017/05/interceptor-missile-defense-test/>

Cold War and DSP Missile Defense Technology

Shortly after World War II, US government scientists investigated the ability to detect and track ballistic missiles using the heat generated during launch. In the mid-1950s, the Air Force selected the Lockheed Corporation to build a satellite equipped with an infrared radiometer and telescope capable of detecting the hot exhaust gases emitted by long-range jet bombers and sizeable rockets as they ascend through the atmosphere. By the end of 1957, Lockheed's proposal was adopted as the Defense Department's overall space-based reconnaissance and surveillance program. By 1958, the system became known as MiDAS, the Missile Defense Alarm System. For a number of years, a constellation of 12 satellites was planned for operation at a 2000-mile altitude above Earth. The next several years were spent in program reviews, development, and feasibility analysis. Finally, by 1966, a series of test launches verified the technology, and the decision was made to construct and deploy a constellation of early warning satellites. The program was eventually designated as the Defense Support Program (DSP). The DSP satellites, with more advanced technology, were to be launched into a geostationary orbit at 22,300 miles above the Earth's surface, allowing constant monitoring of any Soviet and Chinese missile launches.⁶ The DSP system's detection of shorter range offensive and surface-to-air missiles has provided key intelligence on missiles fired during regional conflicts.

The DSP was the US military's first reliable early warning system. These satellites were more capable than their predecessors developed in the MiDAS program. The constellation of DSP satellites is located in geosynchronous orbit, much higher than MiDAS satellite orbits, yielding increased image clarity and continual coverage. Initially begun in 1970, the program has launched a total of 23 DSP satellites over its lifetime. Its technology has improved over the years, resulting in three variants. Early DSP satellites spun around their center axis while in geosynchronous orbit, allowing their telescopic infrared sensor to continuously sweep an area of the planet six times in approximately in 1 minute. Any detected launches or detonation information would immediately be data-linked to controllers on the ground at the 460th Space Wing located at Buckley AFB in Colorado. The DSP constellation was used to detect launches of SCUD missiles during Operation Desert Storm in the Gulf War. However, the resolution accuracy for the location of SCUD launch sites was approximately 2 miles, which was not accurate enough for the mobile launchers to be destroyed. A DSP satellite was launched by the Space Shuttle on STS-44 in 1991 (shown being prepped in Fig. 7.3), and the last one was launched by a Delta IV Heavy lift rocket in 2007.⁷

⁶Richelson, Jeffrey T. [Internet]. The national security archive electronic briefing book no. 235. Space-based early warning: from MIDAS to DSP to SBIRS. 2007. [cited 2017 Oct 26]; Available from: <http://nsarchive2.gwu.edu/NSAEBB/NSAEBB235/index.htm>

⁷NASA, [Internet]. nasa.gov; c2017. DSP, Defense Support Program; [cited 2017 Oct 24]. Available from: <http://space.jpl.nasa.gov/msl/Programs/dsp.html>



Fig. 7.3. STS-44 DSP satellite and IUS during preflight processing at Cape Canaveral.
Image Credit: NASA

A vital component of the DSP system is the ground stations used to analyze the downloaded data and control the satellites. Three major stations were established: the satellites stationed over Eurasia were assigned to the Overseas Ground Station (OGS) at Nurrungar, in the Australian Outback; the Atlantic and Pacific satellites were controlled by the CONUS Ground Station (CGS) at Buckley AFB in Colorado; and later, to monitor and control the European satellites, the European Ground Station (EGS) was set up at Kapaun, Germany. In addition to these stations, a number of mobile ground terminals were built as backups to process DSP data in case of damage to any of the fixed stations.⁸

Since the DSP program was established, the satellites have identified thousands of strategic and tactical missile launches, as well as nuclear detonations in the atmosphere by the French and Chinese. The DSP satellite capabilities have been upgraded over the years. Model DSP-1, first orbited in 1989, had an expected lifespan of 5 years (exceeded) and 6000 detectors. This technology provided far more accurate estimates of missile launches coordinates than was previously possible, an advancement that would have given the US much more accurate information in the event of a nuclear conflict with the Soviet Union.⁹

A priority of the DSP system was for data to be processed as quickly as possible in order to provide important data in case of a possible nuclear conflict with the Soviet Union or other rogue nations. Additionally, the ground stations needed to be more survivable to ensure continuity for transmitted data and analysis. Generations of DSP satellites continued to display their expanded capabilities. A follow-on system was deliberated as early as 1979. However, President Ronald Reagan changed the game plan entirely in 1983 with the creation of the Strategic Defense Initiative. The debates and disagreements that followed over costs and technical requirements for this new program resulted in a large number of DSP follow-on programs being proposed and then canceled for a period of 15 years.

The Strategic Defense Initiative

On March 23, 1983, President Reagan proposed a space-based anti-missile system defined under the Strategic Defense Initiative (SDI). The program was nicknamed “Star Wars” by the popular press, an obvious reference to the popular science

⁸Richelson, Jeffrey T. [Internet]. The national security archive electronic briefing book no. 235. Space-based early warning: from MIDAS to DSP to SBIRS. 2007. [cited 2017 Oct 26]; Available from: <http://nsarchive2.gwu.edu/NSAEBB/NSAEBB235/index.htm>

⁹Richelson, Jeffrey T. [Internet]. The national security archive electronic briefing book no. 235. Space-based early warning: from MIDAS to DSP to SBIRS. 2007. [cited 2017 Oct 26]; Available from: <http://nsarchive2.gwu.edu/NSAEBB/NSAEBB235/index.htm>

fiction movie of the same name that had been released in 1977. The system was specifically intended to defend the United States from Soviet Union missile attacks. Both space- and ground-based laser platforms were proposed as systems equipped to deliver deadly laser strikes and destroy missiles during various phases of their trajectories. A series of sophisticated sensors located on the ground, in airspace, and in outer space orbit would analyze and evaluate threats using radar, optical, and infrared detection systems. Advanced technology for navigation and guidance systems needed to be developed in order to target such a fast-moving object with accuracy.¹⁰

It was thought that a successful demonstration of this technology would give the US a military advantage. Critics, however, were still uncertain about the success rate of such a program and its extremely high cost. Work was started, but the critics were proven correct—the problems were far too complicated, with no technological or financial solutions readily available. Most of the research was cancelled by later administrations.

Reflecting on this initiative years later, one can define two areas of controversy over SDI's proposal and failed implementation. One was political, and the other technological.

SDI would have drastically changed US defense strategy and the accepted understanding of international nuclear defense, summarized by the doctrine of “mutual assured destruction,” or MAD. Adopted at the end of the Kennedy administration, MAD assumes that no country would intentionally launch a nuclear weapon, because the targeted country would respond as long as it had the technology to analyze incoming missiles and launch its own, causing destruction on both sides. Fear of such mutual annihilation would prevent a first strike and keep the peace. In proposing SDI and the creation of a security umbrella, President Reagan was inherently challenging this doctrine, one of many factors discussed by Secretary McNamara in the Kennedy administration. A protective umbrella was superior to MAD, or so Reagan believed: “It was like have two westerners standing in a saloon aiming their guns at each other’s head—permanently. There had to be a better way.”¹¹

SDI provided this protective umbrella, at least in theory, but it was perceived as an aggressive move toward the Soviet Union and put the two nations on the precipice of another arms race. Yet, Reagan was persistent: “[What if] we could intercept and destroy strategic ballistic missiles before they reached our own soil or that of our allies?... Wouldn’t it be better to save lives than to avenge them?”¹² To him, protection seemed the best strategy. Reagan went further, offering to give

¹⁰ [Atomicarchive.com](http://www.atomicarchive.com). [Internet]. c1998-2015. National Science Digital Library; [cited 2017 June 23]. Available from: <http://www.atomicarchive.com/History/coldwar/page20.shtml>

¹¹ Chidester, J., & Kengor, Paul. 2015. Reagan’s legacy in a world transformed. Cambridge, Massachusetts: Harvard University Press. 294 p.

¹² Shimko, Keith L. 1998. The Reagan reversal: foreign policy and the end of the Cold War. *Canadian Journal of Political Science*, 31(4): 824-825.

other nations the SDI technology if they got rid of their weapons arsenal. The initial reaction was one of mistrust. Regardless, the US never reached its goal.

As proposed, SDI would have used space-based lasers, particle beams, satellites, and other space-age weapons to shoot down enemy ballistic missiles before they reached their targets. Placing these weapons in space would require a withdrawal from the Outer Space Treaty of 1967, as they broke Article IV, which states: “State Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or another other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.”¹³

SDI also went against the Anti-Ballistic Missile Treaty (ABM Treaty). Ratified in 1972 as an agreement between the United States and the Soviet Union, the ABM treaty put limitations on the anti-ballistic missile (ABM) systems used in defending against ballistic missile-delivered nuclear weapons. The treaty was in force for 30 years, until the US President George W. Bush withdrew, leading to its termination. “I have concluded the ABM treaty hinders our government’s ability to develop ways to protect our people from future terrorist or rogue-state missile attacks,” President Bush announced, following a meeting with his National Security Council.¹⁴

Russian President Vladimir Putin said that President Bush’s move was not unforeseen, but he considered it a “mistake.”¹⁵ Still, both Bush and Putin agreed that the decision would not weaken Russian national security.¹⁶ The European perspective was a bit different. SDI was seen as a protective umbrella for the United States against Soviet ballistic missiles, but not for the European nations, which were geographically closer and by nature more vulnerable to Russian threats. It appeared that America’s nuclear policy was being changed without informing the allies with whom the policy had been developed, causing surprise and outrage on the European front.¹⁷ Arguments against SDI continuously pointed to the danger of militarizing space and the threat of another arms race.

¹³Treaty on principles governing the activities of the states in the exploration and use of outer space, including the Moon and other celestial bodies. US Department of State. [Internet]. c2017. The Office of Website Management, Bureau of Public Affairs, [cited 2017 June 24]. Available from: <https://www.state.gov/t/isn/5181.htm>

¹⁴Arms Control Association. US withdrawal from the ABM treaty: President Bush’s Remarks and US diplomatic notes. [Internet]. c2017. The Encyclopedia Britannica; [cited 2017 Nov 10]. Available from: www.armscontrol.org

¹⁵The Encyclopedia Britannica, Inc. [Internet]. c2017. The Encyclopedia Britannica; [cited 2017 June 29]. Available from: <https://www.britannica.com/event/Anti-Ballistic-Missile-Treaty>

¹⁶Neilan, Terence. 2001 Dec 13. Bush pulls out of ABM treaty; Putin calls move a mistake. The NY Times (World).

¹⁷Association for Diplomatic Studies and Training. [Internet]. c2017. Moments in US Diplomatic History. The Strategic Defense Initiative – the other “Star Wars”, [cited 2017 July 8]. Available from: <http://adst.org/2015/11/the-strategic-defense-initiative-the-other-star-wars/>

Given SDI's extreme complexity and reliance on unproven technology, both politicians and scientists criticized the program for being too vague and unrealistic. In addition, it was estimated to cost billions of dollars to develop. Figure 7.4 illustrates the basic concept of SDI, which identified several layers of defense to ensure that a missile's payload would never reach its target. This image is a simplification of how weapons in outer space would communicate with surveillance and tracking systems to destroy nuclear warheads being delivered by enemy missiles.

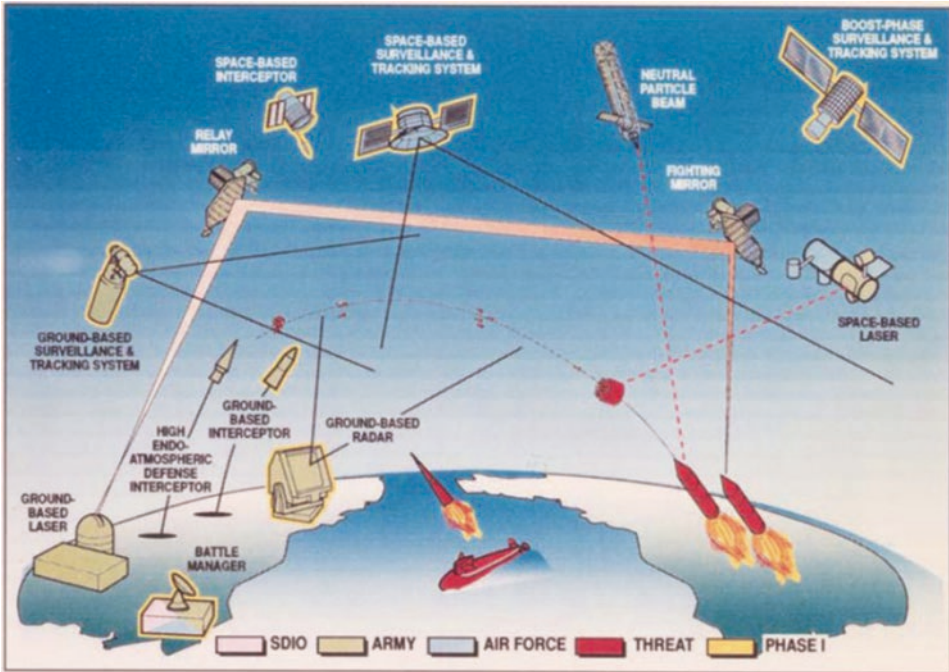


Fig. 7.4. An illustration of the Strategic Defense Initiative (SDI) concept. Image Credit: NASA

What was simply portrayed by this illustration, however, was more difficult to develop and implement in reality. Now, we will look more closely at the SDI implementation concepts and their associated challenges.

SDI Scientific Concepts

SDI provided a layered defense that focused on an incoming missile's three phases of flight: boost, midcourse, and terminal. The United States Army Strategic Defense Command (USASDC) and the Army took the lead in developing the SDI program. The Satellite Defense Initiative Organization (SDIO) funded research on boost surveillance and tracking systems, directed-energy weapons, ground-based

interceptors, radars, command and control systems, and space-based interceptors. Considerable improvements were made in each of these fields. Despite the steady advancement, the program visualized by President Reagan was never fully realized, for reasons that we will discuss shortly.

The boost phase consists of the 3- to 5-minute period from the initial ignition of the missile's rocket to its burnout, which corresponds to a specific trajectory that carries the missile payload up through the atmosphere and into space. A rocket exhibits an exhaust plume, which helps in its initial detection. Nevertheless, speeds can reach up to 15,000 mph, making an accurate intercept very challenging and time critical. After the boost is complete, the nose cone separates from the booster rockets and releases reentry vehicles containing one or more warheads as well as penetration aids consisting of decoys and chaff. The SDI components for the boost phase consist of the Boost Surveillance and Tracking System (BSTS), the Space-Based Laser (SBL) and the Ground-Based Laser (GBL).¹⁸

The original BSTS system required an advanced warning system that could detect launches and track missiles from ignition through burnout phase and provide near real-time data to space-based interceptors. These requirements called for very large optics capable of complex scanning methods and onboard signal and data processing at a level far beyond the capabilities of existing systems. Such an advanced warning system depends first on the development of multilevel, high-resolution sensor technology. Anti-missile systems must have sensor technology with sufficient accuracy to detect and acquire a target. Several layers of sensors work together to create a complete image of the target as it moves through the atmosphere. In addition, the sensors have to discriminate between actual threats, debris, or dummy warheads. The development of sensor technology is further discussed in Chap. 9.

The goal of the BSTS was to detect a missile launch, transmit a warning, and process tracking files for each individual rocket. A host of satellites equipped with sensors and parked in high orbit would monitor the infrared (IR) emissions from the rocket plumes. The sensors, however, would have ended up with poor resolution due to their high altitude. Other sensors at lower altitudes would therefore be required to assist in tracking. Demonstration and validation tests of the technology were needed to evaluate the BSTS's ability to perform required tasks and make a decision on whether to proceed with full-scale development. The significant cost and risk of BSTS development were important factors in the final decision to shelve the effort.¹⁹

The collapse of the Soviet Union at the end of 1991, as well as post-Cold War optimism about international security, led US policies to shift away from a national missile defense system. America turned its focus away from its missile defense program to concentrate on a new concept, Global Protection Against Limited

¹⁸Walker, J. A. 2003. *Seize the high ground: the Army in space and missile defense*. Government Printing Office. 512 p.

¹⁹Walker, J. A. 2003. *Seize the high ground: the Army in space and missile defense*. Government Printing Office. 512 p.

Strikes (GPALS). The US-designed GPALS would be capable of shooting down about 200 reentry vehicles, defined as a limited strike. Substantial improvements and miniaturization in computer electronics and optics made it possible for US engineers and scientists to continue advancing the Reagan-era space-based interceptor concepts. In 1990, these improvements led to the creation of the Brilliant Pebbles system, a concept that replaced the space-based interceptor and formed the core of GPALS. Brilliant Pebbles were small weapons that would intercept enemy missiles and destroy them by force of impact. The idea was to place 10,000–100,000 of these small autonomous units into outer space. Each 45-kg Brilliant Pebble would contain miniaturized sensors and computers to give it the capability required to operate independently of external sensors and communications. The Brilliant Pebbles would track the exhaust of missiles, eliminating most of the need for outside guidance from sensor satellites and ground stations. During the boost phase, the interceptor would strike the incoming missiles when their velocity is the slowest and before they have deployed countermeasures. In addition, the launch countries would have extreme difficulty targeting several thousand small objects in space, as opposed to a few hundred large targets.²⁰ Because the Brilliant Pebble interceptors were to be mass produced, they were expected to be relatively inexpensive, lowering the cost of the first phase of the SDS.²¹

The emergence of miniature space weapons created new options for the Bush Administration as it considered what approach to take on the controversial anti-missile program. Brilliant Pebbles went through several iterations and program changes. By 1992, an operational interceptor was close to demonstrating that it could intercept ballistic missiles and survive in wartime. Congress appropriated funding for the BPI for 1995, but future funding support appeared uncertain. During that decade, interest was shifting away from defense against strategic missiles and toward defense against theater ballistic missiles (between 190 and 2200 mi) launched by third-world countries.²² International players such as North Korea and Iran began improving their ballistic missiles and developing nuclear weapons, which increased threats to US interests both at home and abroad. In spite of the developing threat, President Clinton supported the Anti-Ballistic Missile Treaty and arms control with Russia, formally terminating the SDI program in 1994.²³

²⁰ Broad, W. What's next of 'Star Wars'? New York Times. 25 Apr 1989. P. C1.

²¹ GlobalSecurity.org. [Internet]. c2000-2017. GlobalSecurity.org in the news; [cited 2017 July 15]. Available from: <http://www.globalsecurity.org/space/systems/bsts.htm>

²² Dodge, Michaela. Commentary: space-based missile defense: advancing creativity, protecting lives. 11 Aug 2014. [Internet] [cited 2017 Oct 31]. Available from: <http://spacenews.com/41559space-based-missile-defense-advancing-creativity-protecting-lives/>

²³ Dodge, Michaela. Commentary: space-based missile defense: advancing creativity, protecting lives. 11 Aug 2014. [Internet] [cited 2017 Oct 31]. Available from: <http://spacenews.com/41559space-based-missile-defense-advancing-creativity-protecting-lives/>

A Timeline of Missile Defense Through SDI

1957

The Soviet Union successfully tested its first intercontinental ballistic missile (ICBM) with a reported capability of reaching anywhere in the world. The Russians had already successfully conducted atomic and hydrogen bomb tests, arming them with a weapon of mass destruction capable of being delivered. The Soviets sent the satellite Sputnik into space in October. In the US, apprehension turned to fear that the Russians were beginning to dominate in both the arms and space races. Four months later, the United States successfully launched its first ICBM and started development of its first major anti-ballistic missile (ABM), the Nike-Zeus system, capable of using nuclear-tipped interceptors to destroy incoming enemy warheads in outer space.²⁴

1961

The Soviet Union successfully launched an anti-ballistic missile that intercepted a ballistic missile. The advancement by the Soviets prompted the US to test its own ABM system. Russia and the United States worked on researching and testing ABM defense systems during the next decade.

1972

The United States and the USSR signed the Anti-Ballistic Missile Treaty, which limited each nation to two ABM sites and no more than 100 ABMs. An amendment, added later to the treaty, limited each country to only one missile site.

1983

President Reagan announced that the United States would develop a space-based missile defense system in order to make nuclear weapons “impotent and obsolete.” It was seen as a possible violation of the ABM Treaty and also perceived as technologically unfeasible. The resulting program, the Strategic Defense Initiative (SDI), became known in popular culture as the “Star Wars.”²⁵

²⁴Missile Defense Agency. The US Army’s first anti-ballistic missile. [Internet]. 20 Oct 2009. [cited 2018 May 25]. Available from: <https://www.mda.mil/global/documents/pdf/zeus.pdf>

²⁵Union of Concerned Scientists. [Internet]. c2018. US ballistic missile defense timeline: 1945-today. 18 May 2018. [cited 2018 May 26]. Available from: <https://www.ucsusa.org/nuclear-weapons/us-missile-defense/missile-defense-timeline#.WwnXtu6Uu70>

1986

President Reagan and Soviet President Gorbachev discussed the complete removal of nuclear weapons, but the proposal failed when Reagan refused to agree on any limitations on the SDI program.

1989

President George H.W. Bush decided to maintain the SDI program, while focusing on the development of “Brilliant Pebbles,” a space-based interceptor.

1991

President George H.W. Bush scaled back the SDI program and announced the Global Protection Against Limited Strikes (GPALS) system, which was intended to oppose accidental or small-scale attacks. The plan to launch thousands of small interceptor rockets into orbit was quickly canceled.

1993

Secretary of Defense Les Aspin declared “the end of the ‘Star Wars era’” with the launch of the Ballistic Missile Defense Organization, which focused on national, rather than intercontinental, missile defense.

Reflections

For a time, shooting down enemy missiles heading for US soil was seen as an improbable, futuristic concept. President Reagan’s ideas for a protective umbrella that could prevent first-strike losses were not technologically or economically feasible at the time. As it turned out, the problem was as or more challenging than landing on the Moon. Reagan’s plan called for lasers, enhanced sensors, satellites, impact interceptors, and detailed data analysis to generate accurate target information and destroy incoming warheads. Decades later, the problem has yet to be truly mastered, as the technologies capable of doing so have only been tested on known, scripted targets. The challenge remains an important component in the modern missile defense system.



Post-SDI Missile Defense

“Short of such an explicit threat, the US should take the middle ground by engaging its missile defense system. Within seconds of a North Korean launch, American sensors could analyze the missile’s trajectory and determine whether purpose—most likely either a satellite deployment or an Intercontinental Ballistic Missile (ICBM). If the launch appears to be of an ICBM, the United States should use its missile defense system to destroy the missile.”

–Baker Spring¹

Introduction

Two days after North Korea’s missile launch in May 2017, the US successfully tested its national missile defense system. This was the first hit in almost 3 years. It was also the first time that the system was tested against an ICBM-class target. Ground-based Midcourse Defense (GMD) has cost \$123 billion since 2002, with nine out of 18 successful tests since 1999—exactly 50%.²

¹Spring, Baker. Countering North Korea’s missiles: the missile defense system the US should have. The Heritage Foundation. 21 June 2006. [Internet]; [cited 2017 Nov 05]. Available from: <http://www.heritage.org/defense/report/countering-north-koreas-missiles-the-missile-defense-system-theus-should-have>

²Freedberg Jr., Sydney. GMD missile defense hits ICBM target, finally. 30 May 2017. [Internet]; [cited 2017 Nov 17]. Available from: <https://breakingdefense.com/2017/05/missile-defense-hits-icbm-target-success-rate-now-50/>

Yet so far, the US has not developed the concept of space-based ballistic missile defense interceptors into a successful developed system. Much doubt still remains as to whether or not the concept is technologically or financially feasible. Since 2001, the US has financed its missile defense program at about \$8 billion a year.³ The space-based efforts are focused on advancing systems to give interceptors the ability to discriminate between warheads and countermeasures. Within the past 3 years, with countermeasures utilizing ground-based and space-based satellite data, the Ground-based Midcourse Defense system has successfully intercepted targets that simulated long-range ballistic missiles. Yet today's ground- and sea-based missile defense systems aren't equipped to handle large numbers of incoming ballistic missiles. At this point, there are too few interceptors to do so. National security depends on the ability to intercept all or most ballistic missiles that are headed toward our soil.⁴

This chapter focuses on current missile defense efforts and advancements after the SDI program ended.

Post-SDI Missile Defense

Following the 9/11 attacks, President George W. Bush withdrew the United States from the 1972 Anti-Ballistic Missile Treaty. The administration concluded that it could not depend solely on retaliatory methods when dealing with unstable and unpredictable countries such as North Korea and Iran that were equipped with long-range ballistic missiles. In the following years, the US improved both its ground- and sea-based ballistic missile defense systems, advancing the work of the Strategic Defense Initiative (SDI) Organization, which had been renamed the Ballistic Missile Defense Organization in 1993 and then the Missile Defense Agency in 2002.⁵

In 1995, the Air Force revealed a continuation of the SDI program entitled the Space-Based Infrared System (SBIRS). The program proposed launching four satellites in geostationary orbit, two infrared sensors on highly elliptical-orbiting

³Spring, Baker. Countering North Korea's missiles: the missile defense system the US should have. The Heritage Foundation. 21 June 2006. [Internet]; [cited 2017 Nov 05]. Available from: <https://www.heritage.org/defense/commentary/space-based-missile-defense-advancing-creativity-protecting-lives>

⁴Dodge, Michaela. Commentary: space-based missile defense: advancing creativity, protecting lives. 11 Aug 2014. [Internet] [cited 2017 Oct 31]. Available from: <http://spacenews.com/41559space-based-missile-defense-advancing-creativity-protecting-lives/>

⁵Freedberg Jr., Sydney. GMD missile defense hits ICBM target, finally. 30 May 2017. [Internet]; [cited 2017 Nov 21]. Available from: <https://breakingdefense.com/2017/05/missile-defense-hits-icbm-target-success-rate-now-50/>

National Reconnaissance Office satellites, and a low Earth-orbiting SBIRS that would become a critical component of the national missile defense. The LEO portion of SBIRS has since been renamed the Space Tracking and Surveillance System (STSS). The purpose of the STSS is to follow the trajectories of missiles through all three phases of flight (boost, midcourse, and terminal), distinguish actual warheads from decoys, and transmit data to systems that can direct radar and missile defense interceptors in order to hit their target. Two satellites were launched into LEO in September 2009. These satellites provide an acceptable level of tracking of missile launches, although as many as 30 satellites are required to provide complete coverage of the world.⁶

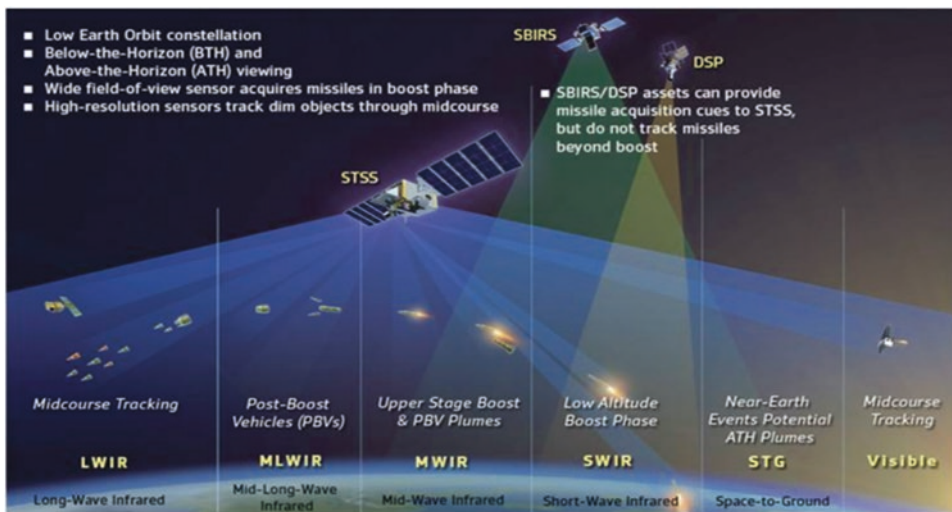


Fig. 8.1. Overview of missile tracking satellite systems. Image Credit: *Missile Defense Advocacy Alliance*

Figure 8.1 illustrates current missile tracking systems. STSS is capable of tracking enemy missiles using the black of space as a background during the midcourse phase of flight, one of the most challenging phases of ballistic missile defense. During the midcourse phase, the missile has launched its weapon payload into lower Earth orbit. The missile falls back to Earth while the warhead travels through space on a ballistic arc that will lead to reentry into the Earth's atmosphere over the intended target. STSS utilizes sophisticated sensors and a signal and data processor to detect enemy ballistic missiles. STSS coordinates its efforts with other US

⁶Horitski, Kristin. Space tracking and surveillance system (STSS). Feb 2016. [Internet]; [cited 2017 Nov 21]. Available from: <http://missiledefenseadvocacy.org/missile-defense-systems-2/missile-defense-systems/u-s-deployed-sensor-systems/space-tracking-and-surveillance-system/>

missile defense and missile tracking systems and is able to relay information that can help guide missile defense interceptors. Once the enemy missile passes into its midcourse phase, a tracking sensor locks onto it as it rockets through space. The sensor also includes a narrowly focused telescope capable of providing coverage above and below the horizon line, allowing it to detect even a faint warhead signal. Other sensors track the missile flying along its trajectory, while the signal and data processor transmits data to ground command centers around the world.⁷

In 2009, the Obama administration began to cut back the Bush administration's funding of homeland missile defense and instead placed more importance on regional defense, particularly in Europe. Due to increasing costs and technical challenges, a number of new programs designed to intercept missiles in their boost phase were canceled. The Defense Department announced in March 2013 that it would strengthen the ground-based midcourse defense (GMD) system in Alaska and California by increasing the number of interceptors from 30 to 44. The system is designed to protect the US against long-range missile attacks from North Korea and Iran. However, with only a 50% success rate, the increase in interceptors is still not adequate to defend against a large-scale attack. The current Missile Defense Agency (MDA) has ramped up efforts to develop a Multi-Object Kill Vehicle (MOKV), which converts each interceptor into multiple warheads fired like a gun at multiple incoming targets. These steps have been taken despite concerns about the technical challenges. The estimated operational date is 2025.⁸

MDA is looking at utilizing lasers for the future, requesting \$54 million in 2018 for Research & Development. Other military branches are involved in testing lasers for short-range defense against the smaller weapons delivered by battlefield rockets and drones, but MDA is required to hit much harder targets at a much longer range. The strategy is to develop a solid-state laser small enough to be launched aboard a drone, which would fly in a circular pattern near a hostile country, target, and kill that country's missiles as they are launched. Solid-state lasers use electricity, allowing for continuous firing as long as there is power.⁹

Another recently tested variation of the GMD system is capable of shooting an Exoatmospheric Kill Vehicle (EKV) above the atmosphere in order to affect incoming warheads while they are still in space. The aim has to be precise, but due to the forces behind such a high velocity collision, there is no need to install an explosive warhead—the EKV blows up the target to bits. When the Ground-based

⁷Arms Control Association. US missile defense programs at a glance. [Internet] [cited 2017 Nov 21]. Available from: <https://www.armscontrol.org/factsheets/usmissiledefense>

⁸Arms Control Association. US missile defense programs at a glance. [Internet] [cited 2017 Nov 22]. Available from: <https://www.armscontrol.org/factsheets/usmissiledefense>

⁹Freedberg Jr., Sydney. GMD missile defense hits ICBM target, finally. 30 May 2017. [Internet]; [cited 2017 Nov 22]. Available from: <https://breakingdefense.com/2017/05/missile-defense-hits-icbm-target-success-rate-now-50/>

Midcourse Defense System identifies a threat with its land, sea, or outer space sensors, it launches a Ground-Based Interceptor aboard a three-stage solid rocket booster to travel out of the Earth's atmosphere at near-hypersonic speeds. After exiting the atmosphere, the kill vehicle homes in on its target. In May 2017, the system destroyed its target in a Missile Defense Agency test over the Pacific Ocean, recording its first intercept of an intercontinental ballistic missile. These intercepts are a tremendous technological challenge (if you recall from earlier, it is what Eisenhower compared to "hitting a bullet with a bullet"), but today that is the standard approach. Although the test doesn't ensure the interceptors will function in a real-world scenario, it does advance the required technology.¹⁰

Directing the EKV to its target requires the communication of a global network of sophisticated sensors, including the controversial Sea-Based X-Band Radar (SBX), a floating platform that analyzes and feeds target data into the Command, Control, Battle Management, and Communication system, which then direct the interceptor to its target. The SBX is a \$2.2 billion, 50,000-ton radar that has become a critical component of the US defense against North Korea and other hostile nations with intercontinental ballistic missile capability. The radar system has been criticized for being ineffective and costly. However, in the most recent test on May 30, 2017, the system performed flawlessly. "SBX performed exactly as designed during this test," said Chris Johnson, the MDA's director of public affairs. "The radar identified the target missile, developed a projected track, discriminated lethal from nonlethal objects, and provided that data to the command and control system, which is exactly how it would perform during an actual scenario."¹¹

Components of Today's US Ballistic Missile Defense System (BMDS)

The current components of the US Ballistic Missile Defense System are illustrated in Fig. 8.2 and described below:

Ground-based Midcourse Defense (GMD): interceptors designed to protect the US against long-range missile strikes.

¹⁰Freedberg Jr., Sydney. GMD missile defense hits ICBM target, finally. 30 May 2017. [Internet]; [cited 2017 Nov 22]. Available from: <https://breakingdefense.com/2017/05/missile-defense-hits-icbm-target-success-rate-now-50/>

¹¹Zimmerman, Malia. Hawaii's X-band radar vindicated by successful missile intercept, military says. Fox News US 08 June 2017. [Internet]; [cited 2017 Nov 30]. Available from: <http://www.foxnews.com/us/2017/06/08/hawaiiis-x-band-radar-vindicated-by-successful-missile-intercept-military-says.html>

Aegis Ballistic Missile Defense (also known as Sea-Based Midcourse): missile defense against short to intermediate-range ballistic missiles; designed to intercept ballistic missiles during post-boost phase and before reentry.

Terminal High Altitude Area Defense: a system designed to intercept and destroy ballistic missiles inside or outside the atmosphere during their final phase of flight. It is capable of rapid deployment and global transport. Hit-to-kill technology using kinetic energy to destroy the incoming warhead.

Patriot Advanced Capability (PAC-3): a land-based element of the BMDS built on the established Patriot missile defense infrastructure, making it the most advanced hit-to-kill-type system. The Army is responsible for the continuing development and production of the PAC-3. Patriot provides the ability to detect, track, and engage short-range ballistic missiles and cruise missiles.

Space-Based Infrared System-High (SBIRS-HIGH): a combination of satellites and their payloads in geosynchronous equatorial orbit (GEO) and highly elliptical orbit (HEO), using ground hardware and software. Delivers early missile warning for the US military Uses using infrared surveillance. One of the nation's highest priority space programs.¹²



Fig. 8.2. Overview of command and control defense systems. Image Credit: *US Department of Defense*

¹² US Department of Defense – Missile Defense Agency (MIL). [Internet] [cited 2017 Dec 22]. Available from: https://www.mda.mil/system/pac_3.html

Potential New Technologies and Looking Forward

The MDA plans to develop and test several new technologies in order to provide the capability to intercept and destroy ballistic missiles during the ascent phase of flight, giving more time and flexibility to target enemy objects. A system called Early Intercept would optimize the ability to assess a target early in its trajectory and eliminate less effective deployment of countermeasures. Additionally, it would reduce the number of interceptors required to eliminate multiple threatening missiles and also minimize the potential impact of debris. The system can provide an extended engagement to assess the attempted intercept, allowing time to shoot again if unsuccessful.¹³

US military defense programs are set to be examined closely by the Trump administration. In August of 2017, President Trump stated, “We are going to be increasing our budget by many billions of dollars because of North Korea, and other reasons having to do with the anti-missile... We are going to be increasing the anti-missiles by a substantial amount of billions of dollars,” he added.¹⁴ Early in November 2017, the Trump White House submitted an amendment for the Fiscal Year 2018 US Department of Defense budget to include an unusually large amount of \$4 billion for missile defense (about half of the US Missile Defense Agency’s total budget request). Over \$2 billion of the requested funds would be put towards the acquisition of 20 additional Ground-Based Interceptors (GBI) to be based at Fort Greely, Alaska. They would be a part of the US Ground-Based Midcourse Defense (GMD) system at that location. Today, GMD is the only US ballistic missile defense system with a limited capability against intercontinental range ballistic missile. The request also includes the purchase of an additional 50 Terminal High Altitude Area Defense interceptors, which could contribute to the defense of Hawaii, Guam, and southern South Korea against short, medium, and intermediate range ballistic missiles.¹⁵

¹³ US Department of Defense – Missile Defense Agency (MIL). [Internet] [cited 2017 Dec 22]. Available from: https://www.mda.mil/system/pac_3.html

¹⁴ Mehta, Aaron. Trump pledges ‘billions’ increase in missile defense spending. DefenseNews. 10 Aug 2017. [Internet] [cited 2018 Jan 3]. Available from: <https://www.defensenews.com/smr/space-missile-defense/2017/08/10/trump-pledges-billions-increase-in-missile-defense-spending/>

¹⁵ Panda, Ankit. The Trump white house seeks an additional \$4 billion for missile defense in fiscal year 2018. The Diplomat. 07 Nov 2017. [Internet] [cited 2018 Jan 3]. Available from: <https://thediplomat.com/2017/11/the-trump-white-house-seeks-an-additional-4-billion-for-missile-defense-in-fiscal-year-2018/>

A Timeline of Missile Defense Post-SDI**1999**

President Clinton signed the National Missile Defense Act of 1999, pledging to deploy a national missile defense system “as soon as technologically possible.” North Korea fired a ballistic missile over Japan.¹⁶

2001

President George W. Bush stated the US intention to withdraw from the ABM Treaty while outlining his concept of an improved national missile defense program. Bush ordered missile defense capabilities to be enabled within 2 years. Russian President Putin aggressively warned the US that the ABM Treaty bans National Missile Defense systems for both nations.

2002

The United States withdrew from the ABM Treaty, leading to its termination. The Ballistic Missile Defense Organization (BMDO) changed its name to the Missile Defense Agency (MDA). President George W. Bush announced the initial development of a ground-based missile defense that would attain functioning capabilities in 2004.¹⁷

2004–2005

Intercept tests of the ground-based midcourse system failed repeatedly.

The first ground-based missile interceptor was installed at an army base in Alaska.

2006–2007

Two target missiles were launched from Kodiak, Alaska and successfully tracked and destroyed by an interceptor launched from Vandenberg Air Force Base in a test of the Ground-Based Midcourse system.¹⁸

¹⁶Union of Concerned Scientists. [Internet]. c2018. US ballistic missile defense timeline: 1945-today. 18 May 2018. [cited 2018 May 26]. Available from: <https://www.ucsusa.org/nuclear-weapons/us-missile-defense/missile-defense-timeline#.WwnXtu6Uu70>

¹⁷Union of Concerned Scientists. [Internet]. c2018. US ballistic missile defense timeline: 1945-today. 18 May 2018. [cited 2018 May 26]. Available from: <https://www.ucsusa.org/nuclear-weapons/us-missile-defense/missile-defense-timeline#.WwnXtu6Uu70>

¹⁸Defense-aerospace.com. [Internet]. c2018. Missile defense exercise and flight test successfully completed. 28 Sept 2007. [cited 2018 May 26]. Available from: <http://www.defense-aerospace.com/article-view/release/86513/us-says-missile-intercepts-incoming-warhead-in-test.html>

2010

A target missile was launched from the Kwajalein Atoll in the Republic of the Marshall Islands. Approximately 6 minutes later, an interceptor was launched from Vandenberg Air Force Base, California. Both the target missile and interceptor performed successfully, however, the Sea-Based X-band radar did not and the interception failed.

In a similar test flight, a two-stage Ground-Based Interceptor (GBI) was launched from Vandenberg Air Force Base, California. The two-stage booster launched an Exoatmospheric Kill Vehicle to a specified point in space.¹⁹

2012

By this time, 30 interceptors had been deployed—four at Vandenberg Air Force Base, California, and the remaining 26 at Fort Greely, Alaska. Tests of the new system failed more often than they succeeded.

2013

The Obama administration committed to increasing the total number of interceptors to 44 by the end of 2017 in response to North Korean threats.

In a flight test of a three-stage Ground-Based Interceptor (GBI) launched from Vandenberg Air Force Base, California, an Exoatmospheric Kill Vehicle was deployed to a designated point in space.

2014

The Pentagon acknowledged, “Iran has publicly stated it may launch a space launch vehicle by 2015 that could be capable of intercontinental ballistic missile ranges if configured as a ballistic missile.”²⁰

2016

North Korea successfully put its second satellite into orbit. Congress considered other missile defense systems to protect against the predicted missile capabilities of North Korea and Iran, as well as Russia and China. In addition, Congress called for the MDA to start the research and development, following with testing and evaluating space-based missile defense programs.

¹⁹Space Archive: 2011 Space and Astronomy News. [Internet]. c2010-2012. Failed missile defense test findings released. 15 Jan 2012. [cited 2018 May 26]. Available from: <http://www.spacearchive.info/news-2011-archive.htm>

²⁰Union of Concerned Scientists. [Internet]. c2018. Pentagon changes its assessment of Iran’s ICBM prospects. 11 July 2014. [cited 2018 May 26]. Available from: <https://allthingsnuclear.org/lgrego/pentagon-changes-its-assessment-of-irans-icbm-prospects>

2017

President Trump stated his plans to develop a state-of-the-art missile defense system.

A successful GMD test took place against an ICBM-range target at an altitude of 3600 mi. The intercept test record was improving to a 50% success rate.

A North Korean missile test indicated that its ICBM might have the capability to reach major US cities.

2018

Congress is asking the Pentagon to investigate the possibility of placing interceptors in space in order to counteract North Korea's testing of more advanced nuclear weapons and delivery systems. The National Defense Authorization Act for Fiscal Year 2018 authorizes the development of a "space-based ballistic missile intercept layer, capable of providing boost-phase defense."²¹

Reflections

The advances in missile defense involve complex layers, sensors, data analysis, and interceptors for all phases of a missile trajectory. What has been learned over the past few decades is just how technologically complex the problem of defending against intercontinental ballistic missiles and their associated decoys and debris can be. The number of spacefaring nations has increased to include more than one nation that has outwardly threatened the security of the United States. The world is on the brink of the weaponization of outer space, but currently, nations have very little to defend against weapons that are used against them or their space property. Perhaps the only choice is to move forward with the development of systems that have proved promising while pursuing more diplomatic options that would prevent the use of weapons in space.

²¹ [Spacenews.com](http://spacenews.com/new-report-slams-idea-of-a-missile-defense-shield-in-space/). [Internet]. c2018. New report slams idea of a missile defense shield in space. 21 Dec 2017. [cited 2018 May 26]. Available from: <http://spacenews.com/new-report-slams-idea-of-a-missile-defense-shield-in-space/>



Satellite Technology

“The eyes of the world now look into space, to the Moon and to the planets beyond, and we have vowed that we shall not see it governed by a hostile flag of conquest, but by a banner of freedom and peace. We have vowed that we shall not see space filled with weapons of mass destruction, but with instruments of knowledge and understanding.”

–John F. Kennedy, 1962¹

Introduction

The world relies on satellite technology for vital communications and entertainment. Over the past 60 plus years, the amount and types of services that satellite networks perform have increased steadily, most often without us realizing it. Systems of manmade objects orbiting above us silently manage basic systems that help us to be safer and more productive. Their entertainment and communication technology control television, telephones, and navigations systems (GPS) used by millions worldwide. In addition, many business and financial transactions between companies and retailers use satellite transmissions to purchase items and services and perform management processes. Further, satellites play a critical role in time-sensitive scientific activities, such as monitoring weather on a global scale and measuring the visual effects of climate and environmental changes, as well as

¹ JFK Library. [Internet] [jfklibrary.org](https://www.jfklibrary.org/JFK/Historic-Speeches/Multilingual-Rice-University-Speech.aspx); Address at Rice University on the nation’s space effort. 12 Sep 1962 [cited 2018 Feb 01]. Available from: <https://www.jfklibrary.org/JFK/Historic-Speeches/Multilingual-Rice-University-Speech.aspx>

providing valuable information in emergency situations. In developing nations, satellites provide access to education and medical expertise. Not as many people are aware of the increasing dependence of military operations on satellite data for surveillance and secure communications.

In order to understand the threat and effects of a war in space, it is important to appreciate the historical development of satellite technology, how satellites operate, and to determine the scientific challenges and successes of satellite applications. This chapter builds on previous ones, describing the past, present, and future technology of satellites, and why they are vulnerable to attack.

Satellite History and Orbits

An artificial satellite is a manmade object in space that orbits the Earth, as opposed to a natural satellite (such as the Moon circling the Earth). Sputnik, launched by Russia in 1957, was the first artificial satellite. The launch was an act that shocked the world and initiated the Space Race between the Soviet Union and the United States. Since that time, satellite technology has progressed rapidly, giving us a wealth of information that helps create, protect, and conserve resources. The ISS is the biggest satellite in orbit (see Fig. 9.1), taking 15 nations over a decade to complete, with plans to be operational until at least 2024.²

The United States' first satellite, Explorer 1, was launched on January 31, 1958 (shown in Fig. 9.2). It was much smaller and lighter than the second Sputnik satellite, and it was the first satellite to carry scientific instruments to collect data.³

The importance and potential of utilizing data accumulated by satellites became obvious as the world benefited from improved weather forecasts, communications, and broadcasts connecting the globe. Scientists could suddenly obtain detailed graphic information of remote locations and changes over time, and the military could utilize enhanced surveillance capabilities. Gradually, more nations became interested in developing and/or launching their own satellites for a variety of reasons. Satellites can have civilian or military purposes, used for science, communications, or surveillance. Depending on the purposes of the satellites, they can be placed in different types of orbits conducive to their tasks.

As described elsewhere in this book, Earth orbits are generally defined by their distance from the Earth's surface and can be categorized by low Earth orbit (LEO), medium Earth orbit (MEO), and high or geosynchronous equatorial orbit (GEO),

²Howell, Elizabeth. [Internet]. [Space.com](https://www.space.com/24839-satellites.html); c2018. What is a satellite?; Oct 26 2017 [cited 2018 Feb 03]; Available from: <https://www.space.com/24839-satellites.html>

³JPL.[nasa.gov](https://www.jpl.nasa.gov/missions/explorer-1/). [Internet]. [jpl.nasa.gov](https://www.jpl.nasa.gov/missions/explorer-1/); c2018. Mission to Earth, Explorer 1. [cited 2018 Feb 03]; Available from: <https://www.jpl.nasa.gov/missions/explorer-1/>



Fig. 9.1. The International Space Station (ISS) photographed from the Space Shuttle Atlantis (November 25, 2009). The ISS is the largest artificial satellite in orbit. Image Credit: NASA

illustrated in Fig. 9.3. Changing a satellite's height also changes its orbital speed. The spacecraft in orbits closer to the Earth move faster. LEO satellite systems are primarily used for data communications. They orbit the Earth at extremely high speeds (one complete orbit taking about 90 minutes) and are not fixed in space in relation to the Earth. Most satellites with scientific applications, including NASA's Earth Observing System convoy, travel in a low Earth orbit.

Military satellites in LEO are typically reconnaissance satellites that can distinguish tanks from a distance of less than 125 mi above the Earth. LEO satellites have very short lifetimes due to the stronger gravitational pull from the Earth, and spacecraft would need some sort of propulsion method to increase their velocity before their orbit decays. Any type of launch vehicle can be used to launch these satellites into orbit.⁴

⁴Riebeek, Holli. Earth Observatory NASA. [Internet]. jpl.nasa.gov; Catalog of Earth satellite orbits. 4 Sep 2009. [cited 2018 Feb 04]; Available from: <https://earthobservatory.nasa.gov/Features/OrbitsCatalog/>

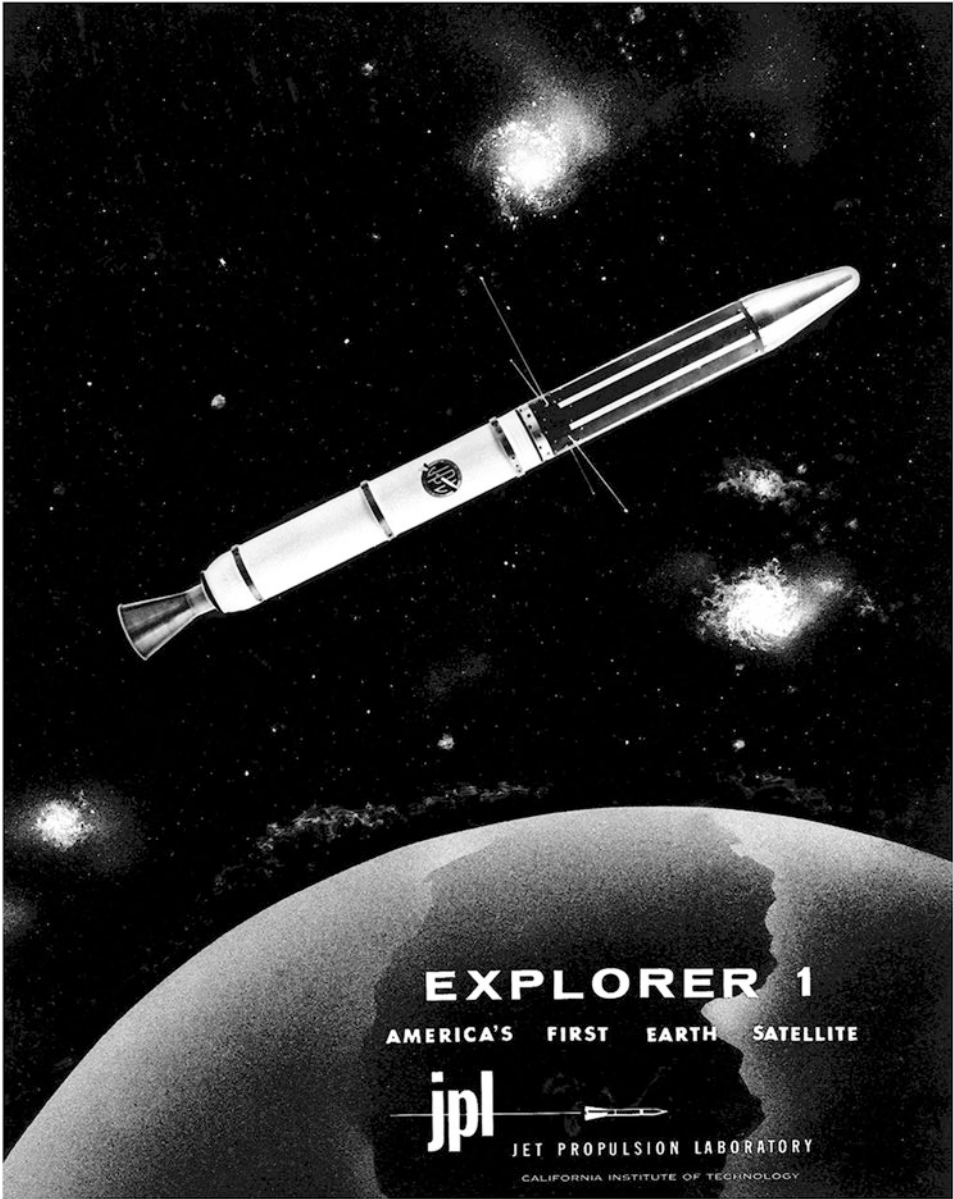
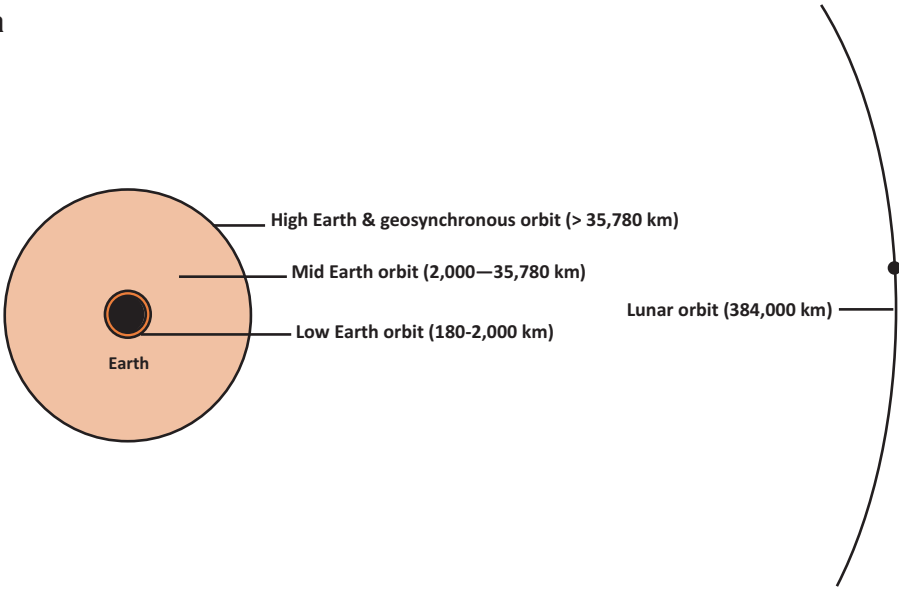


Fig. 9.2. Explorer 1 was the first satellite launched by the US on January 31, 1958.
Image Credit: *NASA/Jet Propulsion Laboratory*

a



b

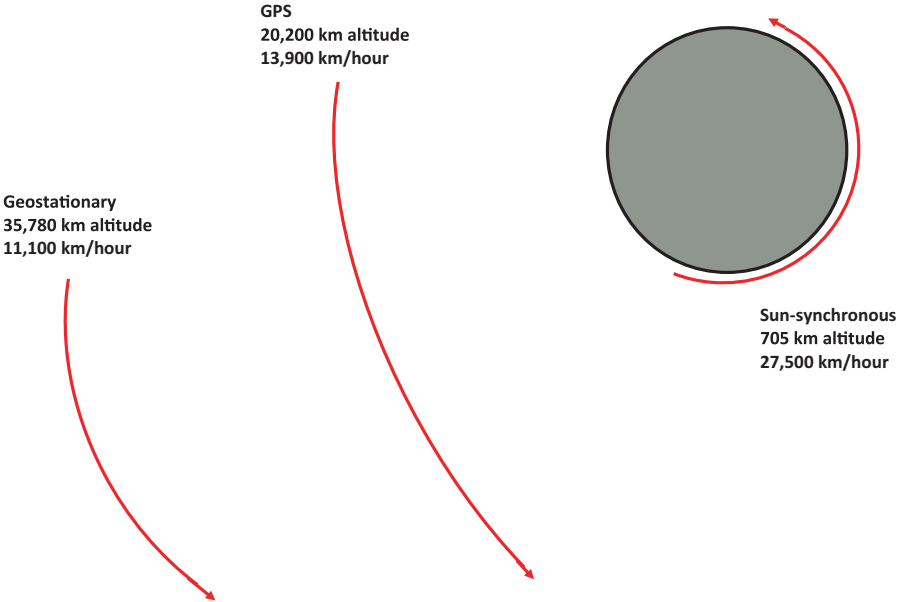


Fig. 9.3. (a, b) Orbits classified by altitude. Image Credit: *NASA/Goddard, illustration by Robert Simmon*

Medium Earth orbit satellites include navigation and specialty satellites intended to surveil or focus communications over a specific region on the Earth's surface. Molniya was a military communications satellite system used by the Soviet Union that orbited in this zone. Russian engineers wanted to use an orbit that consumed less energy and was more suitable for communications than the geostationary orbit favored by the US. A geostationary orbit is stationed over the equator, which doesn't accommodate surveillance over more northern or southern areas of interest. Russian studies suggested an elongated ellipse whose apogee, or the uppermost point, would be over the northern hemisphere, providing nearly uninterrupted viewing of the Russian territory (see Fig. 9.4).⁵

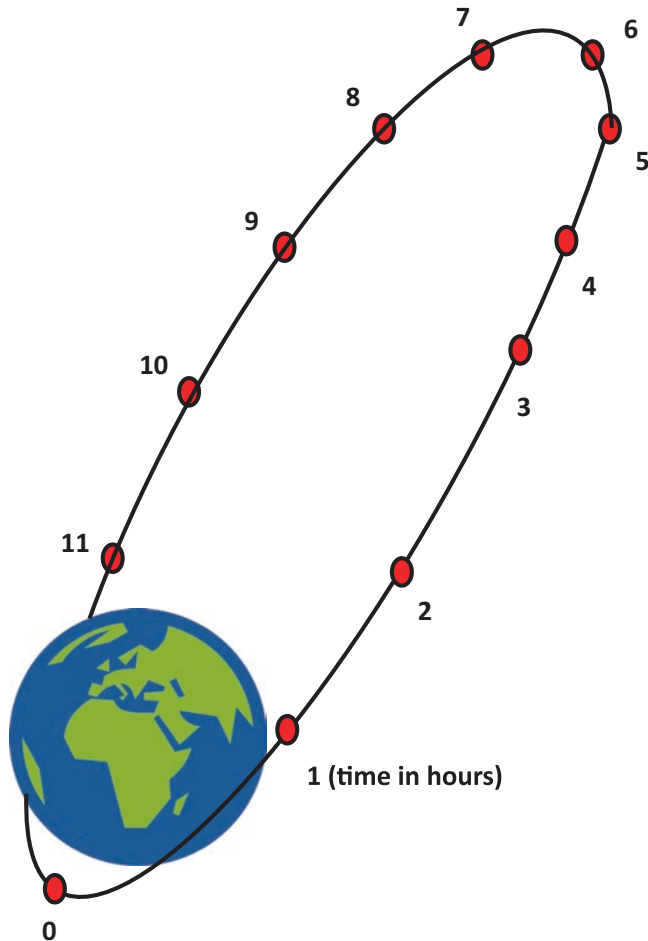


Fig. 9.4. The orbit of Molniya, the Soviet Union's military communications satellite system. Image Credit: [EarthObservatory.nasa.gov](https://earthobservatory.nasa.gov)

⁵[Earthobservatory.nasa.gov](https://earthobservatory.nasa.gov). [Internet] earthobservatory.nasa.gov. Three classes of orbits. c2018. [cited 2018 Feb 04]; Available from: <https://earthobservatory.nasa.gov/Features/OrbitsCatalog/page2.php>

The semi-synchronous orbit is a nearly circular orbit 12,600 mi above Earth's surface. It takes 12 hours for a satellite at this altitude to circle the globe. The Earth is rotating below the satellite while the satellite is orbiting the Earth. Most satellites are orbiting in the same direction as the Earth's rotation. In 24 hours, the satellite in the semi-synchronous orbit traverses over the same two locations on the equator daily. This is the orbit most commonly used by the Global Positioning System (GPS) satellites, a network of navigation satellites made up of at least 24 satellites.

In the early 1970s, the US Department of Defense (DoD) wanted a resilient, stable satellite navigation system for military use. It subsequently launched its first Navigation System with the Timing and Ranging (NAVSTAR) satellite in 1978, made available for civilian use in the 1980s. The system became fully operational in 1993.⁶ Today its legacy, the Global Positioning System (GPS), has become a multi-use, radio navigation system operated by the United States Air Force and owned by the US Government. Its purpose is to aid in national defense and homeland security, along with domestic, commercial, and scientific needs.

The farther away a satellite orbit is from the Earth's surface, the slower the spacecraft travels and the more stable its orbit is in terms of longevity. Meteorological satellites are often placed in sun-synchronous orbits (see Fig. 9.3), where the satellite's orientation is stationary relative to the Sun throughout the year, making precise weather predictions possible. The majority of communications satellites are geostationary satellites, set above one point on the equator of the Earth and taking 24 hours to complete a rotation. This type of satellite orbits at the same velocity that the Earth rotates, keeping it stationary over a single longitudinal point. Most video and television communications networks use geostationary satellites. Geosynchronous and geostationary satellites typically orbit at 22,238 miles above the surface of the planet.⁷ The key difference between the two is that the geosynchronous satellites have a different inclination than those in the geostationary orbit (see Fig. 9.5).

The Tracking and Data Relay Satellite (TDRS) system is positioned in geosynchronous orbit. When geostationary satellites approach the end of their life expectancy, protocol states that they should be maneuvered to a slightly different altitude in order to make room for a new satellite to replace that slot. There are specific locations in that orbit that prevent the satellites operating without interference.⁸

⁶Nasa.gov. [Internet]. [nasa.gov](https://www.nasa.gov/directorates/heo/scan/communications/policy/GPS_History.html); c2017. Global Positioning System history. [cited 2018 Feb 05]; Available from: https://www.nasa.gov/directorates/heo/scan/communications/policy/GPS_History.html

⁷Earthobservatory.nasa.gov. [Internet] [earthobservatory.nasa.gov](https://earthobservatory.nasa.gov/Features/OrbitsCatalog/page2.php). Three classes of orbits. c2018. [cited 2018 Feb 06]; Available from: <https://earthobservatory.nasa.gov/Features/OrbitsCatalog/page2.php>

⁸Riebeek, Holli. Earth Observatory NASA. [Internet]. [jpl.nasa.gov](https://earthobservatory.nasa.gov/Features/OrbitsCatalog/); Catalog of Earth satellite orbits. 4 Sep 2009. [cited 2018 Feb 04]; Available from: <https://earthobservatory.nasa.gov/Features/OrbitsCatalog/>

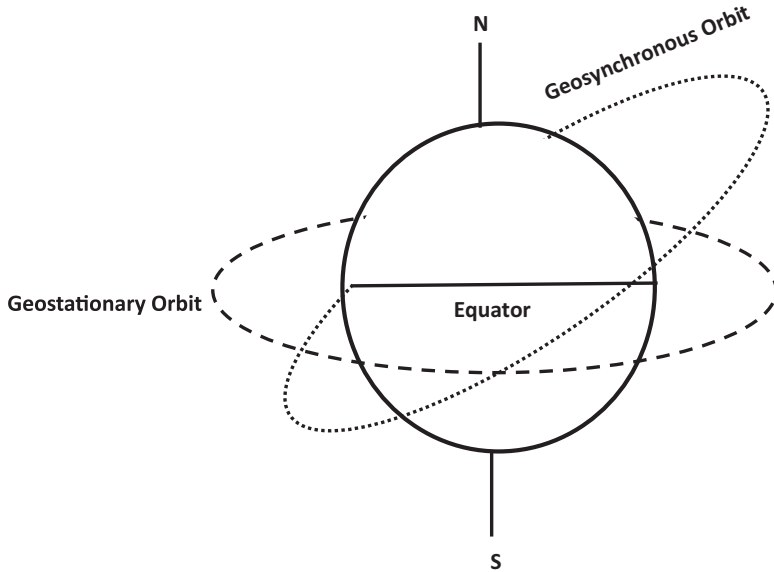


Fig. 9.5. Geostationary versus geosynchronous orbit. Image Credit: polyu.edu.hk

Modern satellites have a mass of several thousand kilograms and are launched into space using vehicles such as the Ariane or Titan Rockets, and most recently, the SpaceX vehicles. Once in outer space, most satellites use solar panels to acquire power from the Sun. Satellites that travel into deep space often use nuclear power. With the miniaturization of computers and other hardware, much smaller satellites can be launched into orbit. Companies and universities can now build “CubeSats,” cube-shaped satellites that regularly occupy low Earth orbit (see Fig. 9.6). These small satellites can be launched by a rocket alongside a bigger payload or can be propelled from a mobile launcher on the International Space Station. NASA is thinking about the possibility of sending CubeSats to Mars or to Jupiter’s moon Europa for future missions.⁹

Satellite Technology

Every usable artificial satellite has a power system (solar or nuclear, for example), a control system, an antenna to transmit and receive information, and a payload used to gather and transmit data. The required technology is described in this section.

⁹Howell, Elizabeth. [Internet]. Space.com; c2018. What is a satellite?; Oct 26 2017 [cited 2018 Feb 03]; Available from: <https://www.space.com/24839-satellites.html>



Fig. 9.6. On left, artist rendering of Montana State University's Explorer 1 CubeSat. On right, a CubeSat created by the University of Michigan. Image Credit: NASA/JPL-Caltech/Montana State University

Cellular Communication Technology

The most common mobile telephony platform is cellular. Cellular communications broadcast and receive data via land-based towers. A single tower creates a cell, which is defined as the coverage area of the tower transmitters. A cellular network consists of a span of towers, each having its own cells (illustrated in Fig. 9.7). When you are in a specific area, your cellular phone utilizes the cell of the nearest tower. If you move away to another area, for example, while traveling in a car, your cell phone transfers to the next available tower. The reason that a signal is weak or that calls are dropped is that the cell tower is too far away or being blocked, resulting in no cell signal or bad reception. Depending on the technology of a cellphone network, a typical cellphone has sufficient power to reach a cell tower up to 45 miles (72 km) away. Sometimes, due to timing of the cellphone protocol, the range can drop to as low as 22 miles (35.4 km).¹⁰ Usually, cellphone signals don't reach these maximum distances due to a variety of factors including obstruction from both natural and unnatural features.

A large number of towers and a complex infrastructure are required to provide complete coverage for cities, an expensive process that may not be readily available in all regions. It is not financially worthwhile for cellular providers to construct cell towers in low-usage areas. It is also difficult or impossible to position towers in very remote or mountainous regions or out in the ocean, making cellular phones pointless for communications in such areas. Although most cities and

¹⁰ Markgraf, Bert. [Internet]. smallbusiness.chron.com; c2018. How far can a cell tower be for a cellphone to pick up the signal?; [cited 2018 Feb 06]; Available from: <http://smallbusiness.chron.com/far-can-cell-tower-cellphone-pick-up-signal-32124.html>

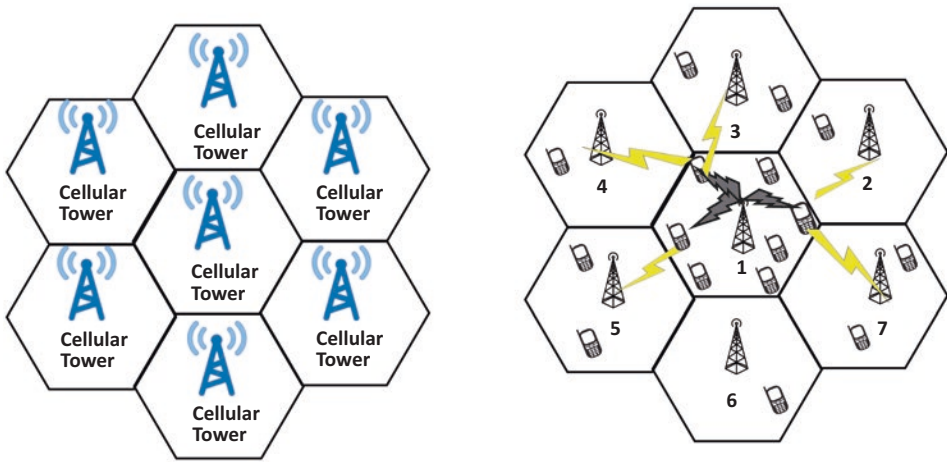


Fig. 9.7. Illustration of cellular technology. Image Credit: vizocomsat.com

congested regions now have access to cellular networks, they still represent less than 50% of the Earth's surface.¹¹ System overload can occur during an emergency, and although there has been improvement, problems still exist. In those circumstances where cellular communications cannot provide the connectivity required, satellite communications step in.

Cellphone signals are in a frequency range that has limited ability to penetrate physical obstructions. Interference weakens the signal, making it unable to access a cell tower that is nearby. Sources of interference can be manmade constructions such as buildings, walls, or tunnels, or natural obstacles such as hills or trees. In urban regions, cellphones that are obstructed from one tower most likely are able to reconnect to another one close by, but in rural areas, when coverage might be restricted to a single cell tower, interference with could make reception unpredictable.¹² The wireless industry has opposed regulations that would harden protections on computer networks, due to the redundancy required to enhance security and reliability. In addition, the industry has opposed some efforts to modernize the emergency response system. Both of these are technologically extensive and expensive to implement, requiring in some case new phones and equipment. Discussions concerning backup power reemerged during emergency procedures for Hurricane Harvey in 2017. "The wireless industry has done everything it can to persuade

¹¹ Baer, Drake. [Internet]. businessinsider.com; 22 Feb 2016. This map shows the percentage of people around the world who own smartphones; [cited 2018 Feb 06]; Available from: <http://www.businessinsider.com/how-many-people-own-smartphones-around-the-world-2016-2>

¹² Staff. [Vizocomsat.com](http://vizocomsat.com). [Internet]. vizocomsat.com; 03 Apr 2016. The difference between cellular and satellite communications; [cited 2018 Feb 06]; Available from: <http://www.vizocomsat.com/blog/difference-cellular-satellite-communications/>

federal regulators and state regulators not to require that backup power be put in place,” said Regina Costa, chair of the telecommunications committee of the National Association of State Utility Advocates, which speaks for consumer representatives. “It’s a huge public safety issue—because in order for communications to work there has to be power.”¹³

Satellite Communication Technology

Satellite communications utilize satellites orbiting the Earth and are therefore not dependent on terrestrial systems. This means that satellite systems are capable of sending/receiving signals over a much wider region. A satellite device can connect to any Earth surface location with satellite beam coverage. The signal from the satellite phone (or other device) links directly to the satellite, which then transmits the signal to the nearest land-based Earth station. The station then broadcasts to the receiving device which can be a landline, cell phone, or another satellite phone. The process is illustrated in Fig. 9.8.

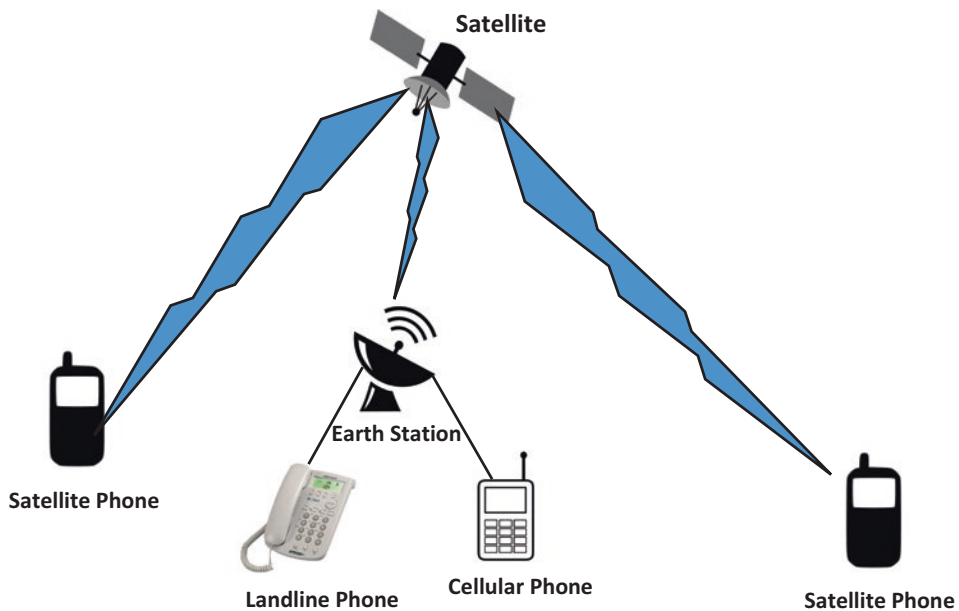


Fig. 9.8. Illustration of satellite technology. Image Credit: vizocomsat.com

¹³ Shields, Todd. Bloomberg.com [Internet]. bloomberg.com; 30 Aug 2017. Harvey knockout of cell service revives talk of backup power. [cited 2018 Feb 06]; Available from: <https://www.bloomberg.com/news/articles/2017-08-30/harvey-s-knockout-of-cell-service-revives-calls-for-backup-power>

Some satellite phones use satellites in geostationary orbit, placed in a stationary position in the sky above the user. These systems can retain nearly continuous global coverage using only three or four satellites, reducing launch and operational costs. The satellites used for these systems are very expensive and heavy to manufacture and launch. The satellites orbit at an altitude of about 22,000 mi. Due to satellite's the long distance from its users, a noticeable delay occurs when making a phone call or using data services.

Signals are transmitted to and from the satellite without relying on towers, making communication useful in remote areas. Still, even if a large swath of open sky is present, the line-of-sight between the phone and the satellite can be obstructed by elevated hills and forests. The user needs to find a location with a clear line of sight before using the phone. Despite potential relay delays, there is substantially more accessible bandwidth on these systems than that of the low Earth orbit systems, making them more suited to high-speed data applications.¹⁴

Mobile satellite communications are clearly more practical than cellular communications for those who are traveling to remote and isolated areas. Figure 9.9 shows the coverage generated by three communications satellites, each encompassing a very wide area. Any mobile satellite device located within a satellite coverage beam is capable of communicating with other satellite devices, regardless of how remote the location on land, sea, or air.

Communication satellites can operate in either an active or passive mode. Passive satellites only reflect signals. The returned signal (referred to as the downlink) can be weakened by power that is limited from the ground station (the uplink), the characteristics of the reflection, and the losses that occur along the channel. Active satellites repeat or analyze signals. A repeater (or transponder) amplifies the radio signals that are uplinked, converts them to a different carrier frequency, and then retransmits them. The resulting amplified signal is much more powerful than one that is passively reflected because the transponder retransmits the entire signal, including noise or interference. A processing satellite receives the uplinked radio signal, demodulates it, potentially reformats the resulting signal, and then remodulates the data onto a new downlink radio signal. The procedure of demodulation eliminates most of the interference and uplink noise before the transmission is downlinked, improving the signal quality.¹⁵

¹⁴ Staff. [Vizocomsat.com](http://vizocomsat.com). [Internet]. vizocomsat.com; 03 Apr 2016. The difference between cellular and satellite communications; [cited 2018 Feb 06]; Available from: <http://www.vizocomsat.com/blog/difference-cellular-satellite-communications/>

¹⁵ Staff. [Aerospace.com](http://aerospace.com). [Internet]. aerospace.com; 01 Apr 2010. Military satellite communications fundamentals; [cited 2018 Feb 06]; Available from: <http://www.aerospace.org/crosslink-mag/spring-2010/military-satellite-communications-fundamentals/>

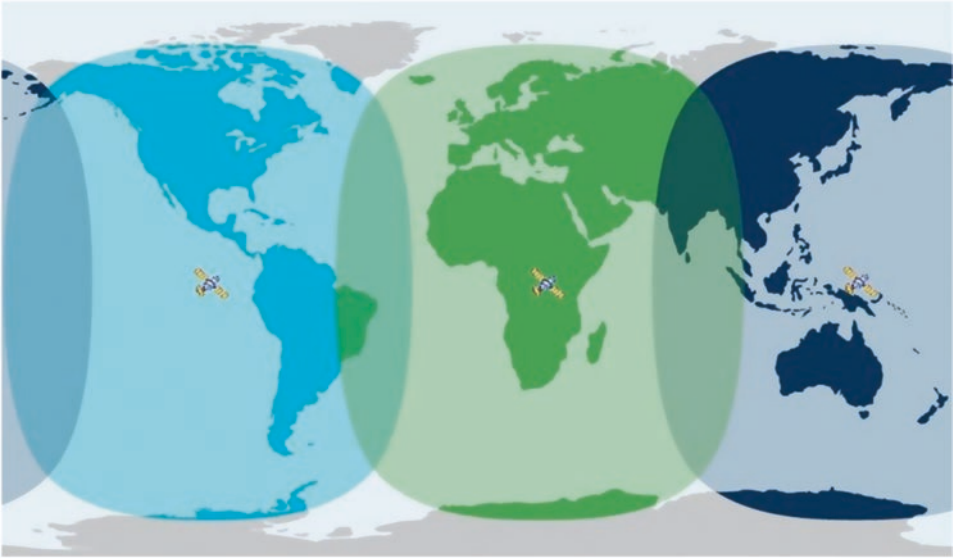


Fig. 9.9. Illustration of satellite technology coverage footprint. Image Credit: vizocom-sat.com

Military Satellite Technology

Military satellite communications have played a vital role in determining wartime strategies with reliable global connectivity. Long before the first manmade satellite reached orbit, scientists and futurists understood the potential of space-based communications. In 1957, the Soviet Union launched Sputnik, the first artificial satellite. A year later, the US Air Force Ballistic Missile Division, the precursor of the Air Force Space and Missile Systems Center (SMC), launched the US Army's Signal Communication (by) Orbiting Relay Equipment (SCORE) into a 101-minute orbit. The payload consisted of adapted commercial equipment fit inside of an Atlas missile fairing (the nose cone that protects a launch vehicle payload against impact), which stored uploaded data to be transmitted later to ground receivers. Before its batteries died, SCORE communicated President Eisenhower's 56-word Christmas wish "for peace on Earth and goodwill toward men everywhere"—the first voice message transmitted from space.¹⁶

¹⁶ Staff. [Aerospace.com](http://aerospace.com). [Internet]. aerospace.com; 01 Apr 2010. Military satellite communications fundamentals; [cited 2018 Feb 06]; Available from: <http://www.aerospace.org/crosslink-mag/spring-2010/military-satellite-communications-then-and-now/>

Courier, the next communications satellite launched by the Department of Defense (DOD) in 1960, was the world's first active repeater satellite. Courier used solar cells to recharge its batteries and was capable of storing data to rebroadcast later. As space technology progressed, military and commercial developers learned from each other's advancements. Commercial enterprise quickly recognized the potential of satellites. The first satellite in geosynchronous orbit (GEO), Syncom 3, was launched in August 1964. It relayed television coverage from the Tokyo Summer Olympics to the United States. Global satellite communications were now a reality. Other space system capabilities were also enabled at this time, including navigation and weather forecasting.¹⁷

In 1962, the Air Force sought private support from the Aerospace Corporation to help develop new systems which would eventually lead to the Initial Defense Communication Satellite Program (IDCSP). The 1964 US Congress decided that US commercial satellite communications systems should be developed separately from military systems because of the military's critical and unique national security requirements. The system's first launches happened in 1966, and ultimately, 26 IDCSP satellites were delivered into a variety of orbits. The 100-pound satellites each had a single repeater. In 1968, when the system was declared operational, its name was changed to the Defense Satellite Communication System (DSCS). Aerospace continued to assist in the planning, development, and operation of the system's components both on the ground and in space.

The military has a trend of using commercial satellites and services when suitable. Over the years, an increased demand for capacity and better security has necessitated more advanced satellite designs. For example, transmitting to tactical ground-based users with small terminals required increased radio transmitter power. The terminals also required additional satellite power, more efficient solar cells, and eventually, a new stabilization technique able to control attitude and allow the capture of more of the sun's energy through improved station-keeping capabilities. It eventually became necessary for ground stations to be able to control a satellite's position and orientation, and, in turn, these requirements led to larger satellites.¹⁸

¹⁷Staff. [Aerospace.com](http://aerospace.com). [Internet]. aerospace.com; 01 Apr 2010. Military satellite communications fundamentals; [cited 2018 Feb 06]; Available from: <http://www.aerospace.org/crosslink-mag/spring-2010/military-satellite-communications-then-and-now/>

¹⁸Martin, Donald, Anderson, Paul, and Bartamian, Lucy. Communication Satellites, 5th Edition. c2004. http://aerospace.wpengine.netdna-cdn.com/wp-content/uploads/2012/03/bk_comm-sats_ch1.pdf

Frequencies

International treaties formulate the rules and regulations for the use of the electromagnetic spectrum with frequencies assigned to designated space systems and specific radio services. US law encompasses these rules and regulations. The International Telecommunications Union oversees the allocation of frequency and specific locations in space for each satellite (see Fig. 9.10 for an illustration of the definitions). Four frequency bands are apportioned in the United States for military space use, including UHF (225–400 MHz), X (7–8 GHz), Ka (30–31 GHz up, 20.2–21.2 GHz down) and EHF (43–45 GHz up, 20.2–21.2 GHz down). The S band (1.761–1.842 GHz and 2.20–2.29 GHz) is shared among all government users. Table 9.1 outlines and describes the frequency bands further. The contents of this table were sourced from the European Space Agency (ESA) website on Telecommunications and Integrated Applications¹⁹:

Table 9.1. Satellite frequency bands

Frequency bands	Frequency (GHz)	Applications
L-band	1–2	Global Positioning System (GPS) carriers; satellite mobile phones; Inmarsat (a company providing communications at sea, land, and air); WorldSpace satellite radio
S-band	2–4	Weather radar; surface ship radar; satellites used by NASA for communication with ISS
C-band	4–8	Satellite communications; full-time satellite TV networks or raw satellite feeds Commonly used in areas subject to tropical rainfall, since it is less vulnerable to fading caused by rain than the Ku band
X-band	8–12	Military applications; radar of the following types: continuous-wave, pulsed, single-polarisation, dual-polarisation, synthetic aperture radar and phased arrays Sub-bands are used in civil, military, and government institutions for weather monitoring, air traffic control, maritime vessel traffic control, defense tracking, and vehicle speed detection for law enforcement
Ku-band	12–18	Satellite communications. In Europe, Ku-band downlink is used from 10.7 to 12.75 GHz for direct broadcast satellite services, such as Astra
Ka-band	26–40	Communications satellites; uplink in either the 27.5 and 31 GHz bands; high-resolution, close-range targeting radars on military aircraft

¹⁹ESA. [Internet]. www.esa.int; c2013. Satellite frequency bands; [cited 2018 Feb 08]; Available from: https://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Satellite_frequency_bands

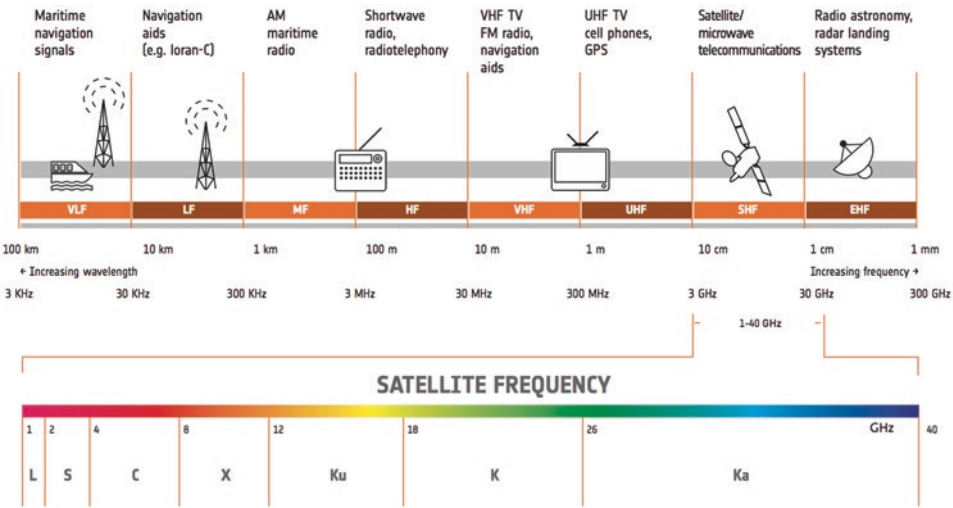


Fig. 9.10. Illustration of satellite technology coverage footprint. Image Credit: ESA

The higher frequencies normally have wider bandwidths, although they are more vulnerable to signal degradation due to rain fade (the effect on radio signals by atmospheric rain, ice, or snow). The lower frequency bands are congested, a critical issue due to the increased number and use of satellites. New technology is being examined so that higher bands can be utilized.²⁰

Satellite technology is developing quickly along with its applications. Satellite use has expanded beyond radio communications and into weather forecasting, broadcasting, astronomy, mapping, and many other applications.

Satellite Communication Technology and Military Use

The benefits and applications of satellite communications were debated after the 1957 launch of Sputnik I. Because of US Congressional concerns of duplication of efforts, NASA focused on experiments with “passive” communications satellites (ECHO), while the Department of Defense concentrated on “active” satellites to provide higher quality communications capable of amplifying the signal received at the satellite. In 1960, AT&T filed with the Federal Communications Commission (FCC) for consent to launch an experimental communications

²⁰ESA. [Internet]. www.esa.int; c2013. Satellite frequency bands; [cited 2018 Feb 08]; Available from: https://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Satellite_frequency_bands

satellite with future plans to deploy a full functioning system. In 1961, NASA awarded RCA a contract to build a medium-orbit (4000 miles) active communication satellite (RELAY). At the time, AT&T was building its own medium-orbit satellite (TELSTAR).

NASA also awarded a contract for a military program, called ADVENT, to Hughes Aircraft Company to build an over 20,000-mile-altitude satellite (SYNCOM). ADVENT became the first main geosynchronous satellite project. It was three-axis stabilized, rather than the previous method using a spinning approach. Its antenna pointed radio energy down toward the earth. Each satellite was complex and heavy. Due to its high weight at 500–1000 pounds, it could only be launched by the more powerful ATLAS-CENTAUR rocket. The ADVENT program was canceled in 1962, due to delays in the CENTAUR stage as well as problems with the required complex technology and cost overruns. Eventually, the satellite issues would be resolved. In the mid-1970s, several satellites were built using the three-axis stabilization approach. Hughes switched its design to this form of stabilization in the early 1990s. Many of the new designs appear comparable to the discontinued ADVENT from the late 1950s.

Despite numerous setbacks, by 1964, two TELSTARs, two RELAYs, and two SYNCOMs were operating successfully in orbit. The Communications Satellite Corporation (COMSAT), formed following the Communications Satellite Act of 1962, was developing its first satellite. COMSAT settled on the 24-hour orbit (geosynchronous) satellite built by Hughes Aircraft Company for its first two systems, and a TRW geosynchronous satellite for its third system. In 1965, EARLY BIRD, COMSAT's first satellite, launched from Cape Canaveral. Global satellite communications were becoming a reality. By that time, communications ground stations already existed in the United Kingdom, France, Germany, Italy, Brazil, and Japan. In 1964, negotiations resulted in a new international organization that would eventually be responsible for the management of the global system. It was called the International Telecommunications Satellite Organization (INTELSAT).²¹

The INTELSAT II series had more capability and a longer life than EARLY BIRD. The INTELSAT III series was the first system to deliver coverage for the Indian Ocean and complete the worldwide network, just days before one half billion people watched Apollo 11 land on the Moon on July 20, 1969.

A lot of the technology required for communications satellites existed in 1960 but would advance over time. The traveling-wave-tube (TWT) was the most commonly used power amplifier in space communications and data transmission systems. The TWT is a specialized vacuum tube used in electronics to intensify radio frequency (RF) signals that occur in the microwave range. The radio wave is

²¹ Whalen, David. [Internet]. history.[nasa.gov](https://history.nasa.gov); c2010. Communications satellites: making the global village possible; [cited 2018 Feb 08]; Available from: <https://history.nasa.gov/satcom-history.html>

strengthened by absorbing power from a beam of electrons as it passes through the tube. Traveling Wave Tube Amplifiers (TWTAs) have been the backbone of the satellite industry for over half a century. The technology was first invented during WWII in England to support high power RADAR transmitters because of its capability of amplifying signals to very high output power levels. This technology was eventually adapted for satellite communications. A major advantage of the TWT over some other microwave tubes is its capability to intensify a wide range of frequencies, yielding a wider bandwidth.²²

High-gain antennas brought another important development to communications satellites. They focus narrow radio beams that accurately target radio signals. High-gain antennas broadcast more power to the receiver, thereby increasing the strength of the signal it receives. Directional antenna signals stay concentrated near the main beam. This property reduces interference.

In early 1976, COMSAT launched a new type of satellite (MARISAT) in order to address delivering mobile services to the United States Navy and other maritime customers. In the early 1980s, the European Space Agency launched the MARECS series to deliver similar mobile services.²³

The latest satellite systems are in orbits at about 500 miles in LEO. Iridium, built by Motorola, is one of the most advanced of these systems. Iridium is expected to launch 66 satellites into polar orbit at altitudes of about 400 miles. Eleven satellites will be placed in six orbital planes, separated by 30° around the equator. In addition to the bigger systems (Iridium and Globalstar), there are several satellites being developed by other companies that offer more limited data services and radiodetermination (the calculation of the position, velocity or other properties of an object by using the propagation of radio waves).²⁴

The Military Strategic and Tactical Relay (MILSTAR) communications system, positioned in geostationary orbit, is operated by the US Air Force and provides secure and jam-resistant communications worldwide for the US military. The multi-satellite constellation will connect ships, submarines, aircraft, and ground stations and their resources to command authorities. Civilian and commercial satellite communications do not contain the same fortified capabilities. The Air Force is currently replacing the MILSTAR system with the Advanced Extremely High Frequency (AEHF) system, a new network of geostationary

²²Damien Minenna, Frédéric André, Yves Elskens, Jean-François Auboin, Fabrice Doveil, et al. *The Traveling-Wave Tube in the History of Telecommunication*. 2018.

²³Whalen, David. [Internet]. history.[nasa.gov](https://history.nasa.gov); c2010. Communications satellites: making the global village possible; [cited 2018 Feb 08]; Available from: <https://history.nasa.gov/satcom-history.html>

²⁴Whalen, David. [Internet]. history.[nasa.gov](https://history.nasa.gov); c2010. Communications satellites: making the global village possible; [cited 2018 Feb 08]; Available from: <https://history.nasa.gov/satcom-history.html>

satellites that will deliver secure relay communications for the US Air Force as well as the armed forces of Canada, the United Kingdom, and the Netherlands. The AEHF system will have the capability to broadcast more than voice and data—it will be able to transmit tactical communications including maps, real-time video, and targeting data solely for military use.²⁵

Branches of the US Armed Forces employ the Defense Satellite Communications System (DSCS), a network of geostationary satellites intended to deliver high-volume and protected voice and data communications. The DSCS has now been operating well beyond its expected lifespan of 10 years. It will be replaced by the Wideband Global SATCOM (WGS) system, a joint venture between the US and Australian governments. The WGS system will support the armed forces of both countries, providing enhanced capabilities in tactical command and control, communications, intelligence, surveillance, and reconnaissance. In addition, the WGS system would make the US and allied forces less dependent on commercial satellite operators for communications services. One of the most vital satellite applications used in military operations (other than GPS) is the use of telecommunications satellites to supply mobile communications with extended line-of-sight capability.

At present, around 80% of all US governmental satellite communications traffic, including the military, is conducted by commercial satellite communications systems. There is a constant need to supplement this capacity by purchasing more bandwidth on commercial satellite systems, even as the capacity steadily increases with the deployment of more military satellite systems. It is critical for the United States and its allies to increase their communications capability in order meet the military requirements intensified by the War on Terror, which has expanded beyond Afghanistan and Iraq.²⁶

The secure satellite communications (SATCOM) equipment used by the US military is currently undertaking performance and volume capability upgrades while, at the same time addressing an increase in security threats. In 2014, the security firm IOActive in Seattle, Washington identified critical design flaws and weaknesses within the firmware of some SATCOM devices that could let distant attackers block, intercept, and possibly take control of significant communications systems used in ground terminals, in the air (except in space), and at sea. “Fortunately, some of the SATCOM devices and related infrastructures are now more secure than two years ago,” says Ruben Santamarta, principal security consultant for IOActive. “There’s been a significant push from companies to

²⁵ Lee, Ricky and Steele, Sarah. 2014. Military use of satellite communications, remote sensing, and global positioning systems in the war on terror. *Journal of Air Law and Commerce*. 79(1/2): 69.

²⁶ Magnuson, Stew. [Internet] nationaldefensemagazine.org. Military not taking advantage of new commercial satellites. 03 Apr 2017; [cited 2018 Feb 08]; Available from: <http://www.nationaldefensemagazine.org/articles/2017/4/3/military-not-taking-advantage-of-new-commercial-satellites>

introduce security into the common life cycles of products. We recommend taking security seriously—by deploying a security development life cycle from the very beginning.”²⁷

Potential security threats are among the reasons that Lockheed Martin engineers designed the Advanced Extremely High-Frequency (AEHF) satellite communications to be one of the world’s most robust satellite communications systems. AEHF serves not only the US but also Canada, the Netherlands, and the United Kingdom. “AEHF provides a necessary assured-communications link for national leaders and military commanders transmitting sensitive information in contested areas,” says Iris Bombelyn, vice president of Lockheed Martin’s Protected Communications mission area in Bethesda, Maryland. Communications satellites must be capable of delivering the demanded bandwidth. “AEHF was designed to significantly increase capacity for the US government,” Bombelyn notes. “Compared to its predecessor Milstar, a single AEHF satellite has a greater total capacity than the entire Milstar constellation.”²⁸

AEHF satellites provide extensive worldwide coverage to facilitate data transfer and provide increased flexibility during worldwide military operations. With enhanced speeds, AEHF “rapidly transmits tactical military communications, such as real-time video, battlefield maps, and targeting data,” Bombelyn says.²⁹

Another company making data capacity advances is ViaSat, who believes that the volume issue is in space, not on the ground. “It’s how the satellite is organized and designed,” says Viasat’s V.P. Goodwin. “Today, we can put more than 700,000 customers on a single satellite. And with ViaSat-2, we’ll double the capacity from ViaSat-1. When the ViaSat-3 constellation launches in 2019, it’ll offer 1 Tbps (terabyte per second) per satellite and will deliver 100 Mbps (megabytes per second) to each user... a conventional satellite does 2 Gbps (gigabytes per second) per satellite, so ViaSat-3 will be 500 times that amount and will give us more flexibility in the service plans we offer,” Goodwin says. Although the data could possibly travel faster, it is not a requirement at this time. The cost of an increased capacity has been a dominant factor over other equipment costs.³⁰

²⁷ Cole, Sally. Military Embedded Systems. [Internet]. mil-embedded.com; 15 Jun 2016. Military secure satellite communications capacity is evolving rapidly; [cited 2018 Feb 010]; Available from: <http://mil-embedded.com/articles/military-communications-capacity-evolving-rapidly/>

²⁸ Cole, Sally. Military Embedded Systems. [Internet]. mil-embedded.com; 15 Jun 2016. Military secure satellite communications capacity is evolving rapidly; [cited 2018 Feb 010]; Available from: <http://mil-embedded.com/articles/military-communications-capacity-evolving-rapidly/>

²⁹ Cole, Sally. Military Embedded Systems. [Internet]. mil-embedded.com; 15 Jun 2016. Military secure satellite communications capacity is evolving rapidly; [cited 2018 Feb 010]; Available from: <http://mil-embedded.com/articles/military-communications-capacity-evolving-rapidly/>

³⁰ Cole, Sally. Military Embedded Systems. [Internet]. mil-embedded.com; 15 Jun 2016. Military secure satellite communications capacity is evolving rapidly; [cited 2018 Feb 010]; Available from: <http://mil-embedded.com/articles/military-communications-capacity-evolving-rapidly/>

The US government is currently examining the structure of military communication networks beyond the designed AEHF 5 and 6. Lockheed Martin is “already working to develop low-cost, follow-on options that leverage economies of scale by using standardized components from commercial satellite contracts,” Bombelyn states. Commercial off-the-shelf (COTS) products in AEHF must first be assessed to determine if they are suitable and robust enough for the environments Lockheed Martin proposes to use them in, according to Bombelyn. “Our mission requires that we are the communications channel that stands when all others fail.”

Quantum Computing for the Future

A promising advance made by China to counter against endless cyberattacks and secure satellite communications may provide the means to a totally secure communications system by converting messages into quantum (a method of encryption) and taking them into space. The new Quantum Space Satellite (QUESS) program is more than a demonstration or experiment. China is already a world leader in quantum communications technology. A satellite that uses quantum communications will employ cutting-edge research into a tactical asset for the benefit of Chinese power.³¹

Cryptography uses an encryption key applied to an encryption algorithm to encrypt or decrypt a message. Quantum entanglement is the act of fusing two or more particles into “quantum states.” Quantum encryption exposes eavesdroppers or hackers. Their identified presence causes quantum states to crumple, revealing the spying to legitimate parties. Quantum uncertainty is the property that allows those participating in secret communications to know if they are being spied on. Because of the complexity of quantum mechanics, it is effectively unfeasible to reverse engineer the quantum key generated by the process of quantum entanglement.³²

A network established in Vienna in 2008 relayed encrypted photons. The required number of repeater hubs to travel long distances made the signal weak and vulnerable to hackers. This network revealed the necessity to communicate via satellite instead. In the vacuum of space, there are almost no atoms to interfere with the quantum signal.³³

³¹ Lin, Jeffrey, Singer, P.W., and Costello, John. Popular Science. 03 Mar 2016. Cryptography forever. Available from: <https://www.popsoci.com/chinas-quantum-satellite-could-change-cryptography-forever>

³² Lin, Jeffrey, Singer, P.W., and Costello, John. Popular Science. 03 Mar 2016. Cryptography forever. Available from: <https://www.popsoci.com/chinas-quantum-satellite-could-change-cryptography-forever>

³³ APS Physics. May 2007 (Vol 15, No. 5). Quantum leap reported for entangled photons. Available from: <https://www.aps.org/publications/apsnews/200705/quantumleap.cfm>

A multi-institutional team of scientists from the Chinese Academy of Sciences, spent over 10 years developing a sophisticated satellite to perform quantum science experiments. The Academy of Sciences claims that the technology “may provide the path to an uncrackable communications system by turning messages quantum and taking them into space.” The satellite Micius, named after an ancient Chinese philosopher, was launched by the Chinese from the Gobi desert in August, 2016. Micius, dedicated to quantum science experiments, orbits at an altitude of close to 310 mi. It is the first satellite of its kind, carrying delicate optical equipment, transmitting to two mountaintop Earth bases separated by 746 mi (see Fig. 9.11). The optics onboard are key components to distributing the particles, or photons, of light that can encode the “keys” to secret messages transmitted to the ground stations. The Chinese have proven that a spaced-based network using quantum technology is possible.³⁴

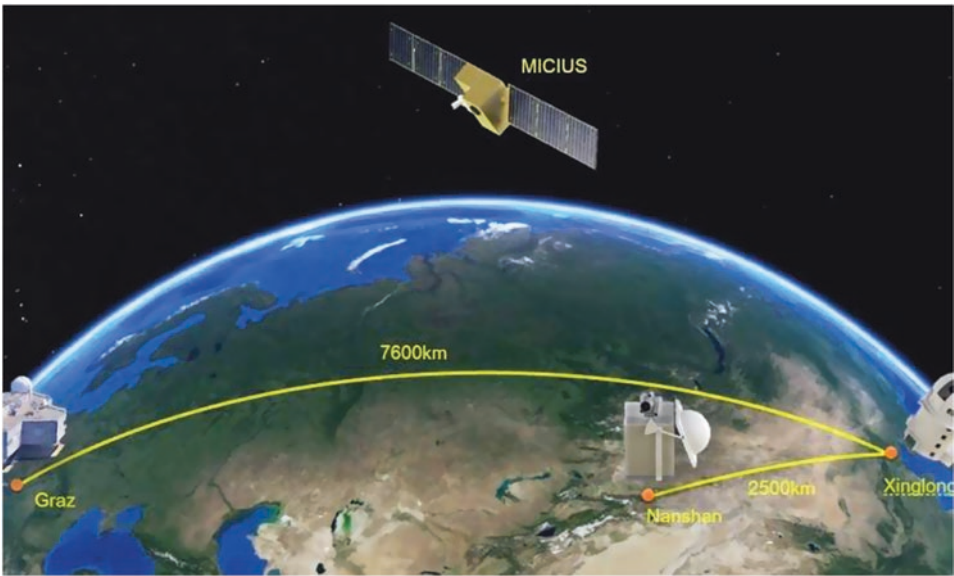


Fig. 9.11. Illustration of the three cooperating ground stations (Graz, Nanshan, and Xinglong) used by the Micius satellite for key generation. Image Credit: *University of Science and Technology of China*

Does the US have its own objectives for safeguarding its military satellite communications using quantum technology? So far, it has yet to be revealed. “Although I can’t specifically discuss quantum communications, safeguarding and preserving our satellites and their missions is of the utmost importance, and continued

³⁴Pease, Roland. BBC News. [Internet]. bbc.com; 15 Jun 2017. China’s quantum satellite in big leap; [cited 2018 Feb 012]; Available from: <http://www.bbc.com/news/science-environment-40294795>

advancement in protective technologies by the entire industry must remain a top priority,” says Lockheed Martin’s Bombelyn. The biggest challenge Bombelyn foresees for military communications is to deliver systems capable of handling a variety of threats from enemies at a reasonable price. “Solving this problem will require combining design solutions from our commercial satellite systems, common satellite components, and new technologies,” she says. “Space has typically been a cooperative environment, with spacefaring entities working together for the greater good. With new entrants to this arena, the future is unclear.”³⁵

Remote Sensing Technology

Remote sensing involves observing and measuring items on the Earth’s surface from a distance. It started as aerial photography, images taken by cameras using a variety of methods—balloons, birds, airplanes, even kites—as early as the 1800s. The term “remote sensing” was first used in 1960 when new methods and technologies were advancing beyond photography. The ability to carry instruments was also shifting from airplanes to satellites into the 1970s, as more land could be monitored on a consistent basis. In addition, imagery shifted from analog to a digital format, allowing computer technology to process and analyze data in both graphic and numerical formats. Sensors became available that allowed analysis of the electromagnetic spectrum beyond human eye vision. The detected electromagnetic (EM) radiation was a combination of reflected solar radiation and radiation emitted by objects on the Earth’s surface.³⁶

Today, many satellites, with a variety of remote sensing instrumentation, monitor the Earth’s surface. The Landsat (Earth Resources Technology Satellite) Program is a series of Earth-observing satellite missions jointly managed by NASA and the US Geological Survey. The Landsat satellites were inspired by Apollo photographs of the Earth’s land surface taken from space. In a 1966 press release, Secretary of the Interior Stewart L. Udall announced the start of “Project EROS,” a program “aimed at gathering facts about the natural resources of the Earth from earth-observing satellites carrying sophisticated remote sensing observation instruments.”³⁷ Landsat was first launched in 1972 and continues to the present day, with Landsat 9 scheduled to launch in 2020.

³⁵ Cole, Sally. Military Embedded Systems. [Internet]. mil-embedded.com; 15 Jun 2016. Military secure satellite communications capacity is evolving rapidly; [cited 2018 Feb 010]; Available from: <http://mil-embedded.com/articles/military-communications-capacity-evolving-rapidly/>

³⁶ Remote sensing. Rai Technology University. http://164.100.133.129:81/eCONTENT/Uploads/Remote_Sensing.pdf

³⁷ Landsat. [Internet]. landsat.usgs.gov; c 2018 What is Landsat and when did it begin; [cited 2018 Feb 012]; Available from: <https://landsat.usgs.gov/what-landsat-and-when-did-it-begin>

The sensors on Landsat 1 transformed remote sensing. They provided imagery in both digital and a multi-spectral format. The instruments onboard the Landsat satellites have collected millions of images from their missions. They provide valuable data for global change research and applications in the fields of regional planning, agriculture, geology, forestry, and education. Landsat data are downlinked to ground stations across the world and archived at the USGS EROS Center.

America's first military satellite program was called CORONA, a secretive reconnaissance program that continues to the present day through more advanced Keyhole satellites and Landsat monitoring programs. CORONA was worked on from 1959 to 1972 but remained unknown to the American public until 1995, when President Clinton ordered the declassification of the imagery, which aided environmental studies. The CORONA Program was created during the Cold War to help determine the strength of the Soviet Union, with respect to its numbers of bombers and intercontinental missiles (ICBMs). The U-2 bomber spy plane flew at 70,000 ft., carrying high-resolution cameras in the late 1950s and into the 1960s and provided valuable information about troop movements in various parts of the world. However, the U-2s were still vulnerable to attack, and it was recognized that a reconnaissance system based on orbiting satellites was preferred. Outer space was not included in the traditionally denied airspace for aircraft and so for the time being was not targeted. The first successful CORONA satellite system in 1960 started the age of space reconnaissance and advanced remote sensing. By 1972, it had acquired over 800,000 images. Even though the CORONA satellites provided valuable images, there were problems retrieving film capsules that were parachuted back to Earth and caught in midair by an airplane. In addition, there were delays of days and sometimes weeks between the initial image capture and release of the film capsule. For time-sensitive military events, this was unacceptable.³⁸

The Keyhole reconnaissance satellites continued after the CORONA Program ended. The new Keyhole satellites have real-time coverage, record images day and night, and transfer digital images electronically. A Keyhole (KH) satellite has a large orbiting digital camera with an exceptionally large lens. It is similar to the Hubble telescope, except that it faces back toward Earth about 200 miles below. A charge coupled device (CCD) gathers images that generate digital photographs for transmission back to Earth. The black-and-white images are used by both military and civilian groups. A lot of the details concerning this class of satellites remain classified, but it is known that there are several orbiting above Earth at

³⁸ Lan, Sharon Watkins Lang. US Army. [Internet]. [army.mil](https://www.army.mil); 18 Aug 2016. Project Corona: America's first photo reconnaissance satellite; [cited 2018 Feb 012]; Available from: https://www.army.mil/article/173155/project_corona_americas_first_photo_reconnaissance_satellite

any given time. They have an imaging resolution of 5 in. Corona satellites, the earlier system that conducted mapping of the Earth from space, had an imaging resolution of 6 ft.³⁹

Reflections

Arthur C. Clarke had a vision in 1945 of an arrangement of three “manned” satellites located over landmasses on Earth’s surface that provided live broadcast television.⁴⁰ Although this hasn’t happened in the same manner as his vision, satellites do provide us with television and so much more, as described in this chapter. Mapping analysts create 3D images of structures and land formations on the ground by using satellite data. These images are valuable resources for both civilians and the military. Or, as in the case of the television broadcast, the images can prove the truth about some activity on the ground. Such images were once used to observe the underside of an orbiting space shuttle and detect missing ceramic tiles, vital to be intact for reentry.⁴¹

In the United States, Vandenberg Air Force Base in California has been the main site to host the launch of many surveillance satellites during the Cold War up to the present day. Some early satellites contained capsules onboard that would return film canisters back to the Earth. The canisters were grabbed in the air by Air Force crews over the Pacific Ocean. We have moved beyond these mechanical retrieval methods to the direct transmission of data and images back to Earth for both civilian and military use. However, only a limited number of countries possess the ability to develop a satellite. Furthermore, only about 14 countries have the capability to launch a satellite using their own rockets (Russia, USA, China, UK, France, Canada, Japan, India, Israel, Ukraine, Iran, North Korea, South Korea, New Zealand) and one regional organization (the European Space Agency/ESA).⁴²

³⁹Tarantola, Andrew. Gizmodo. How the US built its super-secret spy satellite program. 23 Apr 2013 <https://gizmodo.com/5994202/how-the-us-built-its-super-secret-spy-satellite-program>

⁴⁰Whalen, David. [Internet]. history.nasa.gov; c2010. Communications satellites: making the global village possible; [cited 2018 Feb 08]; Available from: <https://history.nasa.gov/satcom-history.html>

⁴¹Whalen, David. [Internet]. history.nasa.gov; c2010. Communications satellites: making the global village possible; [cited 2018 Feb 08]; Available from: <https://history.nasa.gov/satcom-history.html>

⁴²Webster dictionary.

The “War on Terror” and its associated conflicts involve the biggest extent of the military use of satellite applications and the largest US government investment in military and space assets since the Cold War. It has provided the present-day impetus for greater militarization of space and cyberspace—not a new political tactic by any means. Increasing demands on satellite applications by US military have hastened the progression of advanced satellite technologies and the expansion of commercial capacity. The military has become the largest customer for commercial and dual-use satellite applications.⁴³

⁴³ Lee, Ricky and Steele, Sarah. 2014. Military use of satellite communications, remote sensing, and global positioning systems in the war on terror. *Journal of Air Law and Commerce*. 79(1/2): 69.



Preventing a War in Space

“The strength of a civilization is not measured by its ability to fight wars, but rather by its ability to prevent them.”

—Gene Roddenberry, *Earth: Final Conflict*, February 7, 2000.¹

Introduction

A new race involving the commercialization and potential weaponization of space is accelerating. Recent technological advancements and overt testing over the past several years demonstrate increased international competition to achieve dominance in outer space. At the same time, it is renewing concerns that a war could occur in that arena, resulting in widespread devastation. We depend on space systems for navigation, communication, and exploration, as well as a multitude of other functions essential to modern life. The disabling of several key satellites is enough to introduce chaos into basic Earth operations that rely on communication and timing. If aggressive weapons are used, the resulting debris would most likely destroy surrounding spacecraft, creating more damaging debris in a chain reaction. The world economy could be shattered. In fact, the aftermath of space warfare could be equivalent to that of a nuclear war.

The United States and other nations are preparing for a potential war in space. However, the emphasis will most likely be on prevention. Being a leader in military space technology provides enormous advantages to the US, but reliance on

¹ Shown at the end of the episode “Scorched Earth”, no. 14 in the third season of Gene Roddenberry’s *Earth: Final Conflict*, first aired on February 7, 2000. <https://www.military.com/veteran-jobs/career-advice/military-transition/famous-veteran-gene-rodtenberry.html>

those technologies entails risks. In fact, it is hopeful that the predicted costs of a space war on the entire world might be sufficient to discourage the US from launching its own space war.

The United States will stay focused on deterrence as the militarized space race continues. A war in space would be destructive to all facets of life, and avoiding it, rather than discovering new ways to fight it, will likely remain the goal. The previous chapters have described how outer space would be used as a theater of war and what the effects would be. This chapter summarizes the resulting efforts.

Dependence on Space Assets

Space is becoming congested and technologically competitive (see Fig. 10.1). Since the Soviet Union launched the first satellite into orbit in 1957, no nation has purposely obliterated another nation's spacecraft in orbit. But the required technology has been demonstrated, and the possibility exists that battles could soon be fought in space. In addition, space assets can be used to monitor hostile missile launches and provide valuable data for a defensive missile or another object used to shoot down the attacker.

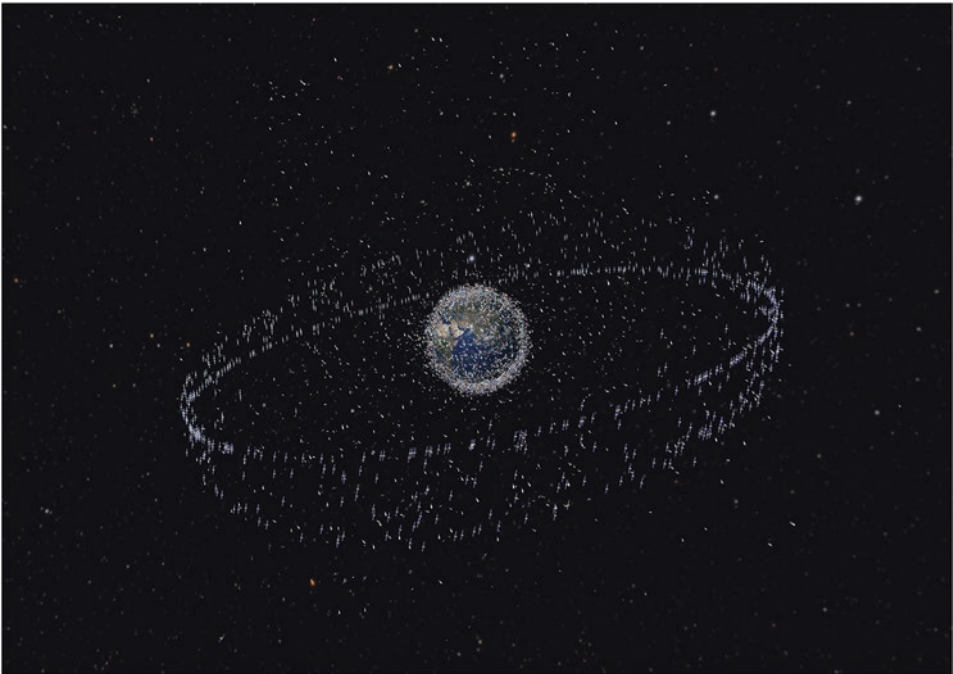


Fig. 10.1. An artist's impression based on actual orbital density data. Image Credit: *European Space Agency*

The move toward the weaponization of space is quickening. US competitors are developing and deploying anti-satellite weapons (known as ASATs and described in Chap. 2). The required technology for ASATs began developing during the Cold War and, over decades, has launched an intense rivalry between the world's most accomplished militaries.²

The United States has demonstrated its leadership in military space technologies. But as pointed out, these advantages, coupled with the nation's reliance on those technologies, can be hazardous. Dependence on space assets gives US enemies motivation to attack the US infrastructure in orbit.

The US military relies heavily on its orbital assets to support critical activities such as communication, navigation, precision targeting, intelligence collection, and early warning. China and Russia are less dependent on their assets than the US, even though they also rely on space to some degree. First, both China and Russia currently have much fewer spacecraft in orbit. Second, because both nations are focused more on their immediate geographic regions, they are able to use more conventional tools, rather than high-tech ones, to accomplish their objectives. For instance, Beijing, because of its geographic vicinity, could rely on its ground-based radars and sensors for a conflict occurring in the Taiwan Strait. The US on the other hand would have to utilize its satellites in order to support a conflict in the same location or any region geographically distant.³

Despite the United States' superior ability to strike at enemy spacecraft, competing nations might conclude that the resulting loss of space assets would be worthwhile if it meant severely diminishing US outer space capabilities. The United States orbiting resources do have some vulnerabilities and limitations. Satellites in orbit follow expected movements, have restricted maneuverability, and are challenging to defend from an attack.

A full-blown kinetic strike on US satellites would cause substantial physical damage while inviting a shattering reaction. There are other tactics intended to reduce the satellites' abilities, rather than to demolish the spacecraft, that would be stealthier and might be worth the risk. These methods include hacking operational software, jamming signals, and dazzling (temporarily blinding) or permanently disabling sensors. It might be worth it to deliver nonkinetic strikes and create a small amount of physical damage that could even be reversed when stopped. A potential enemy could take advantage of the United States' hesitance to intensify a conflict in space, given that it is so heavily dependent on orbital technology.⁴

²Lamrani, Omar. Worldview. 17 May 2016. Avoiding a war in space. [Internet] [cited 2018 Apr 222]; Available from: <https://worldview.stratfor.com/article/avoiding-war-space>

³MacDonald, Bruce W. CSR No. 38. Sep 2008. China, Space Weapons, and U.S. Security.

⁴STRATFOR. Business Insider. 18 May 2016. How the U.S. can avoid a war in space. [Internet] [cited 2018 Apr 222]; Available from: <http://www.businessinsider.com/how-the-us-can-avoid-a-war-in-space-2016-5>

Preventing a War in Space

At the same that the United States negotiates to dissuade hostilities in outer space, it is also facing reality and preparing for the possibility of a full-fledged war in space. The Department of Defense has chosen the secretary of the U.S. Air Force as the principal adviser for an initiative to coordinate space-related efforts across the military. In late 2015, the United States also founded the Joint Interagency Combined Space Operations Center at Colorado's Schriever Air Force Base. The center analyzes data and runs a series of war game scenarios in order to simulate battles in orbit. It also expedites information sharing across the national security space enterprise.⁵

The Pentagon has added billions to its space programs budget towards technologies and strategies that can facilitate the prevention or recovery from a space attack. One method, being developed by the Operationally Responsive Space Office, is to design and build small satellites and associated launch systems capable of being assembled and deployed quickly and inexpensively. The current US fleet of satellites consists of large, complex, and expensive satellites costing upwards of a few billion dollars, many taking years to construct. The office has also directed the development of a modular, more standardized satellite framework towards this effort that accepts numerous payload variations, in the hopes of achieving greater flexibility, lower costs, and a faster turnaround in manufacturing production. The next step is to develop a more efficient and less expensive method to launch replacements for disabled or destroyed systems. Keeping this objective in mind, the Operationally Responsive Space Office is funding the development of the Spaceborne Payload Assist Rocket-Kauai (SPARK) launch system, which plans to send miniaturized satellites into low Earth and sun-synchronous orbits. The US military is also hoping to influence the private sector to participate in its efforts to rapidly launch large numbers of miniaturized satellites cheaply. Companies such as Virgin Galactic (with the LauncherOne) and the Rocket Lab (with the Electron Vehicle) have conveyed an intense interest in the enterprise.⁶

The small satellite modernization assures that disabled satellites will swiftly be replaced in the case of an attack, which is necessary to secure the US military's use of satellite networks in support of operations during a conflict. Small satellites are not the magical solution. Critical satellite functions will still rely on bulkier and more complex systems, such as the larger nuclear-hardened command-and-control mission satellites. Hefty antennas and sizeable power sources are loaded onto these types of systems.⁷

⁵Lamrani, Omar. Worldview. 17 May 2016. Avoiding a war in space. [Internet] [cited 2018 Apr 22]; Available from: <https://worldview.stratfor.com/article/avoiding-war-space>

⁶Lamrani, Omar. Worldview. 17 May 2016. Avoiding a war in space. [Internet] [cited 2018 Apr 22]; Available from: <https://worldview.stratfor.com/article/avoiding-war-space>

⁷Lamrani, Omar. Worldview. 17 May 2016. Avoiding a war in space. [Internet] [cited 2018 Apr 22]; Available from: <https://worldview.stratfor.com/article/avoiding-war-space>

The preferred method of preventing war in any environment is a combination of demonstrating a show of force while working diligently to reinforce diplomacy. This book has summarized the US defense programs and the capabilities that missiles have to attack enemy threats. Overall, the United States is seriously preparing for the threat posed by space warfare. It is expanding its investments in new technologies, slowly developing the organizational architecture necessary to deal with such an eventuality. Aggressive ASAT capabilities do not wholly guarantee an advantage. However, if they are successful, they will deny critical access to space during a catastrophic space war.

One indication of this new sense of urgency is President Donald Trump's recent and repeated calls to establish a "Space Force"—a separate military branch that would be tasked with keeping America as a leader in space, a role played primarily by the Air Force. "My new national strategy for space recognizes that space is a war-fighting domain, just like the land, air and sea," Trump said in June 2018. "We have the Air Force, we'll have the space force." Trump's new National Security Strategy, issued late last year, singled out space as a "vital interest" for the first time and encouraged the military to "advance space as a priority domain." It also said that "Any harmful interference with or an attack upon critical components of our space architecture that directly affects this vital US interest will be met with a deliberate response at a time, place, manner, and domain of our choosing."⁸ The Trump administration's latest budget requested allocated \$12.5 billion for military space efforts, not including secret projects. The US will thus concentrate on Secretary of the Air Force Heather Wilson calls a "more dependable architecture" for the four Air Force satellites that provide early warning of missile launches. They are critical in establishing US readiness in one of the most treacherous regions, the Korean Peninsula. "We stare at the Earth and look for the telltale signs of a rocket launch and within seconds, detect that launch and detect where it's heading and alert the National Command Center," she explained. "So whenever the television shows that picture of North Korea launched a missile, that arc actually comes from the Air Force."⁹

Another focus of the new initiative will be to defend the Air Force's 31 Global Positioning System satellites. "The Air Force provides GPS for the world, for about 1 billion people every day," Wilson continued. "In this budget," she added, "we've proposed to upgrade GPS to what we call GPS III, which is more resistant to jamming." More recently, Russia has employed GPS and satellite jammers to

⁸Bender, B. & Klimas, K. Politico 06 April 2018. Space war is coming and the US is not ready. [Internet] [cited 2018 22 Aug]; Available from: <https://www.politico.com/story/2018/04/06/outer-space-war-defense-russia-china-463067>

⁹Bender, B. & Klimas, K. Politico 06 April 2018. Space war is coming and the US is not ready. [Internet] [cited 2018 22 Aug]; Available from: <https://www.politico.com/story/2018/04/06/outer-space-war-defense-russia-china-463067>

try to interrupt space communications in the eastern Ukraine conflict, Weeden said. “In that sense, it’s already a part of conflict on Earth.”¹⁰

The Pentagon is investing in new technologies that give the military the ability to track, in real time, all space assets. Additionally, they make certain that the two dozen military communications satellites relying on an advanced frequency cannot be jammed. “We must expect that war of any kind will extend into space in any future conflict, and we have to change the way we think and prepare for that eventuality,” Air Force chief of staff Gen. David Goldfein said early in 2018.

Currently, there is no existing method to clear the deadly space junk clouds created by a future shooting war. The United States should do more work to publicize a more preventive perspective with its global partners and allies, showing how a full-blown battle would destroy orbiting satellites and result in a situation that is bad for all of humanity.

“You can’t control all of space all the time,” Wilson said in an interview. “Just the physics of space is so different than the others. These analogies start to break down.” For example, she said that a satellite by definition is a “sitting duck...It is the brightest thing in the sky, with a predictable orbit, with nowhere to hide.” In her view, approaching outer space in the same way as other regions where conflict is inevitable is also risky and dangerous. “These are sensationalist views, and if you keep beating that inevitability drum long enough, you can work yourself into it,” said Johnson-Freese, author of *Space Warfare in the 21st Century*. “We need to have a policy of strategic restraint,” Wilson advised.¹¹

The biggest challenge of space defense is building capabilities that aren’t mistaken or pre-emptively used as offense. A war in space will obviously be catastrophic to all on Earth, and preventing it, rather than discovering ways to fight it, will likely remain the goal.

Strategies to Deter Attacks

The United States needs to capitalize on approaches to prevent attacks on its orbital assets. One step to intensifying space deterrence is identifying the responsible parties. If an attack on a satellite occurs, for example, the US would be unable to hold its enemies accountable if it does not know or has no way of proving who was behind it. It is virtually impossible to monitor the entirety of orbital space around

¹⁰ Bender, B. & Klimas, K. Politico 06 April 2018. Space war is coming and the US is not ready. [Internet] [cited 2018 22 Aug]; Available from: <https://www.politico.com/story/2018/04/06/outer-space-war-defense-russia-china-463067>

¹¹ Bender, B. & Klimas, K. Politico 06 April 2018. Space war is coming and the US is not ready. [Internet] [cited 2018 22 Aug]; Available from: <https://www.politico.com/story/2018/04/06/outer-space-war-defense-russia-china-463067>

Earth. In addition, along with the trouble with obtaining physical evidence from satellites under attack, it is also difficult to prove who is responsible.

One of the promising surveillance systems is the second-generation Space Fence, described in Chap. 4, which will stand as an enhanced defense to track satellites and orbital debris. Slated to begin operations by the end of 2018, Space Fence will use round-based radars that provide ten times the detection capability of its previous system, the Air Force Space Surveillance System. Additionally, the United States has been working with a classified satellite defense technology called the Self-Awareness Space Situational Awareness system, which will allegedly be able to locate the source of a laser fired at a satellite.¹²

The built-in redundancy of sophisticated backup systems that exists on large satellite constellations could deter possible attackers. Certain assaults would not bring considerable harm to US space control, while they would put the attacker at danger of being exposed, inviting retaliation. The widespread use of filters, surge arresters, resistant antenna designs, and fiber-optic components, which are less vulnerable to attack, is currently being investigated to further advance shielding satellites from jamming, dazzling, and blinding.¹³

At the same time, the US has been exploring alternative options to some of the core functions provided at present by satellites alone, given that our unimpeded access to orbit may be interrupted during a war in space. High-flying unmanned aerial vehicles carrying satellite-like payloads are one of the most advanced alternatives. However, this solution remains tentative due to the vehicles' vulnerability to sophisticated air defenses and their limited global reach.¹⁴

Reflections

Space warfare has been a fundamental aspect of science fiction for decades. Real-world fears were somewhat lessened by the 1967 Outer Space Treaty, which banned the use of nuclear weapons in outer space. However, the treaty doesn't explicitly ban the use of conventional weapons in space. Thus, Russia began its first anti-satellite weapons program in 1961. After the Cold War ended, fears about space conflict slowly let up.¹⁵

¹²Lamrani, Omar. Worldview. 17 May 2016. Avoiding a war in space. [Internet] [cited 2018 Apr 22]; Available from: <https://worldview.stratfor.com/article/avoiding-war-space>

¹³Lamrani, Omar. Worldview. 17 May 2016. Avoiding a war in space. [Internet] [cited 2018 Apr 22]; Available from: <https://worldview.stratfor.com/article/avoiding-war-space>

¹⁴Lamrani, Omar. Worldview. 17 May 2016. Avoiding a war in space. [Internet] [cited 2018 Apr 22]; Available from: <https://worldview.stratfor.com/article/avoiding-war-space>

¹⁵Ignatius, David. The Washington Post. 16 Mar 2017. [Internet] [cited 2018 Apr 22]; Available from: https://www.washingtonpost.com/opinions/war-in-space-is-becoming-a-real-threat/2017/03/16/af3c35ac-0a8f-11e7-a15f-a58d4a988474_story.html?noredirect=on&utm_term=.d04da39719ad

China's 2007 test of an anti-satellite missile, which destroyed a Chinese target in space and created more than 3000 dangerous pieces of debris, was a wakeup call about the dangers of space junk travelling at high speeds. The Chinese have conducted a total of eight satellite-killer rocket tests. Russia, too, has resumed similar tests. Rocket attacks against satellites are probably less concerning than electronic ones. Satellites could use jammers to disrupt other satellites. Ground systems can already create "electronic bubbles" that block GPS signals. As on Earth, hackers pose a hidden danger. Orbits can be altered; sensors can be disrupted; data can be contaminated.¹⁶

The challenges to deter a war in space are many. Several aspects of a space war are no different from a war on Earth. Technology and a show of force are important strategies for establishing power. These assets, however, necessitate other types of technology for proper defense and security.

Outer space is still seen as the next great area for humans to explore. Our manned missions to the Moon and our presence in low Earth orbit are a very small step to exploring the vast universe. Unmanned probes explore the outer reaches of the Solar System, reporting back their findings and expanding our scientific understanding. In the midst of peaceful space exploration is the undercurrent of competition between nations and a sense that pristine celestial bodies can be exploited for power or monetary value.

Many US space missions have had a dual purpose: the peaceful accumulation of scientific data to benefit all mankind, and the use of space and its objects to gain an upper hand on enemy activities and even carry out military operations in a covert manner. It is not surprising that other spacefaring nations have similar dual missions in order to keep up with the changing nature of space applications and to maintain power and security.

It is clear from the aggressive activities of the present international players in the field that the United States is right to continue building upon its dual goal of establishing security and defense and expanding scientific discovery and space exploration of the worlds beyond.

¹⁶Ignatius, David. The Washington Post. 16 Mar 2017. [Internet] [cited 2018 Apr 222]; Available from: https://www.washingtonpost.com/opinions/war-in-space-is-becoming-a-real-threat/2017/03/16/af3c35ac-0a8f-11e7-a15f-a58d4a988474_story.html?noredirect=on&utm_term=.d04da39719ad

Appendix A: United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (1967)¹

The States Parties to this Treaty,

Inspired by the great prospects opening up before mankind as a result of man's entry into outer space,

Recognizing the common interest of all mankind in the progress of the exploration and use of outer space for peaceful purposes,

Believing that the exploration and use of outer space should be carried on for the benefit of all peoples irrespective of the degree of their economic or scientific development,

Desiring to contribute to broad international cooperation in the scientific as well as the legal aspects of the exploration and use of outer space for peaceful purposes,

Believing that such cooperation will contribute to the development of mutual understanding and to the strengthening of friendly relations between States and peoples,

Recalling resolution 1962 (XVIII), entitled "Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space", which was adopted unanimously by the United Nations General Assembly on 13 December 1963,

Recalling resolution 1884 (XVIII), calling upon States to refrain from placing in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction or from installing such weapons on celestial bodies, which was adopted unanimously by the United Nations General Assembly on 17 October 1963,

¹United Nations. [Internet]. United Nations treaties and principles on outer space. 2008; [cited 2018 May 24]. Available from: http://www.unoosa.org/pdf/publications/st_space_11rev2E.pdf

Taking account of United Nations General Assembly resolution 110 (II) of 3 November 1947, which condemned propaganda designed or likely to provoke or encourage any threat to the peace, breach of the peace or act of aggression, and considering that the aforementioned resolution is applicable to outer space,

Convinced that a Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, will further the purposes and principles of the Charter of the United Nations,

Have agreed on the following:

Article I

The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind. Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies. There shall be freedom of scientific investigation in outer space, including the Moon and other celestial bodies, and States shall facilitate and encourage international cooperation in such investigation.

Article II

Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.

Article III

States Parties to the Treaty shall carry on activities in the exploration and use of outer space, including the Moon and other celestial bodies, in accordance with international law, including the Charter of the United Nations, in the interest of maintaining international peace and security and promoting international cooperation and understanding.

Article IV

States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner. The Moon and other celestial bodies shall be used by all States Parties to the Treaty exclusively for peaceful purposes. The establishment of military bases, installations and fortifications, the testing of any type of weapons and the conduct of military manoeuvres on celestial bodies shall be forbidden. The use of military personnel for scientific research or for any other peaceful purposes shall not be prohibited. The use of any equipment or facility necessary for peaceful exploration of the Moon and other celestial bodies shall also not be prohibited.

Article V

States Parties to the Treaty shall regard astronauts as envoys of mankind in outer space and shall render to them all possible assistance in the event of accident, distress, or emergency landing on the territory of another State Party or on the high seas. When astronauts make such a landing, they shall be safely and promptly returned to the State of registry of their space vehicle. In carrying on activities in outer space and on celestial bodies, the astronauts of one State Party shall render all possible assistance to the astronauts of other States Parties. States Parties to the Treaty shall immediately inform the other States Parties to the Treaty or the Secretary-General of the United Nations of any phenomena they discover in outer space, including the Moon and other celestial bodies, which could constitute a danger to the life or health of astronauts.

Article VI

States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty. When activities are carried on in outer space, including the Moon and other celestial bodies, by an international organization, responsibility for compliance with this Treaty shall be borne both by the international organization and by the States Parties to the Treaty participating in such organization.

Article VII

Each State Party to the Treaty that launches or procures the launching of an object into outer space, including the Moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such object or its component parts on the Earth, in air space or in outer space, including the Moon and other celestial bodies.

Article VIII

A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body. Ownership of objects launched into outer space, including objects landed or constructed on a celestial body, and of their component parts, is not affected by their presence in outer space or on a celestial body or by their return to the Earth. Such objects or component parts found beyond the limits of the State Party to the Treaty on whose registry they are carried shall be returned to that State Party, which shall, upon request, furnish identifying data prior to their return.

Article IX

In the exploration and use of outer space, including the Moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the Moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty. States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose. If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the Moon and other celestial bodies, would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment. A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party in outer space, including the Moon and other

celestial bodies, would cause potentially harmful interference with activities in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, may request consultation concerning the activity or experiment.

Article X

In order to promote international cooperation in the exploration and use of outer space, including the Moon and other celestial bodies, in conformity with the purposes of this Treaty, the States Parties to the Treaty shall consider on a basis of equality any requests by other States Parties to the Treaty to be afforded an opportunity to observe the flight of space objects launched by those States. The nature of such an opportunity for observation and the conditions under which it could be afforded shall be determined by agreement between the States concerned.

Article XI

In order to promote international cooperation in the peaceful exploration and use of outer space, States Parties to the Treaty conducting activities in outer space, including the Moon and other celestial bodies, agree to inform the Secretary-General of the United Nations as well as the public and the international scientific community, to the greatest extent feasible and practicable, of the nature, conduct, locations and results of such activities. On receiving the said information, the Secretary General of the United Nations should be prepared to disseminate it immediately and effectively.

Article XII

All stations, installations, equipment and space vehicles on the Moon and other celestial bodies shall be open to representatives of other States Parties to the Treaty on a basis of reciprocity. Such representatives shall give reasonable advance notice of a projected visit, in order that appropriate consultations may be held and that maximum precautions may be taken to assure safety and to avoid interference with normal operations in the facility to be visited.

Article XIII

The provisions of this Treaty shall apply to the activities of States Parties to the Treaty in the exploration and use of outer space, including the Moon and other celestial bodies, whether such activities are carried on by a single State Party to

the Treaty or jointly with other States, including cases where they are carried on within the framework of international intergovernmental organizations. Any practical questions arising in connection with activities carried on by international intergovernmental organizations in the exploration and use of outer space, including the Moon and other celestial bodies, shall be resolved by the States Parties to the Treaty either with the appropriate international organization or with one or more States members of that international organization, which are Parties to this Treaty.

Article XIV

1. This Treaty shall be open to all States for signature. Any State which does not sign this Treaty before its entry into force in accordance with paragraph 3 of this article may accede to it at any time.
2. This Treaty shall be subject to ratification by signatory States. Instruments of ratification and instruments of accession shall be deposited with the Governments of the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America, which are hereby designated the Depositary Governments.
3. This Treaty shall enter into force upon the deposit of instruments of ratification by five Governments including the Governments designated as Depositary Governments under this Treaty.
4. For States whose instruments of ratification or accession are deposited subsequent to the entry into force of this Treaty, it shall enter into force on the date of the deposit of their instruments of ratification or accession.
5. The Depositary Governments shall promptly inform all signatory and acceding States of the date of each signature, the date of deposit of each instrument of ratification of and accession to this Treaty, the date of its entry into force and other notices.
6. This Treaty shall be registered by the Depositary Governments pursuant to Article 102 of the Charter of the United Nations.

Article XV

Any State Party to the Treaty may propose amendments to this Treaty. Amendments shall enter into force for each State Party to the Treaty accepting the amendments upon their acceptance by a majority of the States Parties to the Treaty and thereafter for each remaining State Party to the Treaty on the date of acceptance by it.

Article XVI

Any State Party to the Treaty may give notice of its withdrawal from the Treaty 1 year after its entry into force by written notification to the Depositary Governments. Such withdrawal shall take effect 1 year from the date of receipt of this notification.

Article XVII

This Treaty, of which the Chinese, English, French, Russian and Spanish texts are equally authentic, shall be deposited in the archives of the Depositary Governments. Duly certified copies of this Treaty shall be transmitted by the Depositary Governments to the Governments of the signatory and acceding States.

IN WITNESS WHEREOF the undersigned, duly authorized, have signed this Treaty.

DONE in triplicate, at the cities of London, Moscow and Washington, D.C., the twenty-seventh day of January, one thousand nine hundred and sixty-seven. 9 1 Resolution 2222 (XXI), annex. B.

Appendix B: Additional Resources for Space Warfare Topics

Chapter 1: Life Without Satellites

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Chapter 2: Space as the Next Theater of War

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Chapter 3: The Environment of Space as a Theater of War

NASA: Space Technology Grand Challenges:

https://www.nasa.gov/pdf/503466main_space_tech_grand_challenges_12_02_10.pdf

A Researcher's Guide to: Space Environmental Effects: 2015.

https://www.nasa.gov/sites/default/files/files/NP-2015-03-015-JSC_Space_Environment-ISS-Mini-Book-2015-508.pdf

Jakhu, Ram and Pelton, Joseph. Global Space Governance: An International Study: Space Environmental Issues 2017. pp 435–477. Springer.

Chapter 4: Space Debris as a Weapon

Hall, Loretta. The History of Space Debris. 06 Nov 2014. Embry-Riddle Aeronautical University Scholarly Commons. [Internet] [cited 2018 May 30]; Available from:

<https://commons.erau.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1000&context=stm>

Aerospace Company. An Overview of Orbital Debris. 2017. [Internet] [cited 2018 Jun 01]; Available from:

<http://aerospace.wpengine.netdna-cdn.com/wp-content/uploads/2017/09/OrbitalDebrisOverview.pdf>

Chapter 5: A Summary of the US Space Program and Its Relationship to the Military

An Early History of Satellites 1950–1978

<https://www.jpl.nasa.gov/infographics/infographic.view.php?id=11182>

History of Satellites Timeline:

<https://www.sciencelearn.org.nz/resources/1905-history-of-satellites-timeline>

Timeline of Space Exploration

<http://www.localhistories.org/spacetime.html>

National Archives: Space Exploration

<https://www.archives.gov/research/alic/reference/space-timeline.html>

Timeline: 50 years of spaceflight

<https://www.space.com/4422-timeline-50-years-spaceflight.html>

Chapter 6: Who Controls Space and How

Full text of all of the United Nations treaties regarding the use of outer space:

UNITED NATIONS OFFICE FOR OUTER SPACE AFFAIRS

United Nations Treaties and Principles on Outer Space

United Nations, New York 2008

http://www.unoosa.org/pdf/publications/st_space_11rev2E.pdf

Full text of H.R.2262—U.S. Commercial Space Launch Competitiveness Act—2015

114th U.S. Congress (2015–2016)

<https://www.congress.gov/bill/114th-congress/house-bill/2262/text>

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Chapter 7: The Cold War and Missile Defense

An historical perspective of missile defense and space:

Walker, J. A. 2003. *Seize the High Ground: the Army in Space and Missile Defense*. Government Printing Office. 512 p.

Chapter 8: Post-SDI Missile Defense

An historical perspective of missile defense and space:

North Atlantic Treaty Organization (NATO) Ballistic Missile Defence

Last updated: 15 May 2018

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Chapter 9: Satellite Technology

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Chapter 10: Preventing a War in Space

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Appendix C: Space Defense Terms and Programs and Their Historical Context

Anti-Satellite (ASAT) Systems

Weapons designed to disable or entirely destroy satellites in low Earth orbit. The United States, Russia, and China are believed to have successfully developed and tested either directed- or kinetic-energy ASAT weapon systems. ASAT systems can be based on land or mounted on aerial platforms.¹

Historical Context

The early US and Soviet missile interceptors were equipped with nuclear weapons, whose large lethal range would have made ASAT or anti-ballistic-missile (ABM) successful without requiring precision guidance. However, nuclear explosions in space destroy all surrounding spacecraft, making this an unfavorable option.

The Russian ASAT system utilized a co-orbital strategy, where a spacecraft equipped with conventional explosives, such as shrapnel, could be launched into the target satellite's orbit, positioning itself near enough to destroy its target. After conducting a series of tests from 1963–1971, the Soviet Union declared the system operational in 1973.

The following timeline is taken with permission from the Union of Concerned Scientists.²

¹Maini, Anil K. 2018. *Handbook of Defence Electronics and Optronics: Fundamentals, Technologies, and Systems*. New Jersey: Wiley Publishers. Chapter 5, Military Satellites; p. 461.

²Union of Concerned Scientists. [Internet]. *A History of Anti-Satellite Programs (2012)*; Feb 2012. [cited 2018 Aug 14]. Available from: <https://www.ucsusa.org/nuclear-weapons/space-security/a-history-of-anti-satellite-programs#.W3M6Gc4zq70>

Table C.1 History of anti-satellite programs

1972	The Anti-Ballistic Missile (ABM) treaty, an agreement between the US and the Soviet Union, prohibited defenses against strategic ballistic missiles
1976	The Soviet Union resumed testing of its Co-Orbital ASAT system. It was functional until 1993
1983	President Reagan announced his goal to develop a large-scale missile defense system called the Strategic Defense System (SDI) program, nicknamed “Star Wars.” SDI would develop several types of space-based interceptors with ASAT ability. The Soviet Union restarted the design of its own missile defense systems while offering peaceful negotiations in the form of a proposed ban on space-based weapons and a delay on its own ASAT weapons testing
1984	The US began testing the Air-Launched Miniature Vehicle (ALMV), a two-staged missile launched from an F-15 aircraft flying at high altitude. The missile would climb to a target satellite in low Earth orbit, destroying or damaging it in a high-speed collision, a method known as a “kinetic kill” or “hit-to-kill” strategy. Destroyed satellites would create hundreds of fragments of space debris, generating more disastrous high-speed debris
1985–1987	US Congress banned further testing of the system on satellites in 1985, and the Air Force discontinued the program in 1987
Late 1980s	The US Air Force and Navy began developing an anti-satellite ground-based laser system. Intelligence suggested that the Soviet Union was also working on a laser system capable of destroying spacecraft and missiles. The laser could attack using a variety of levels of intensity that could temporarily or permanently damage parts of a satellite’s sensor, or use high power to damage or destroy a satellite
1990s	The Navy combined its Mid-Infrared Advanced Chemical Laser (MIRACL) with a large mirror to direct the laser beam. The US Army planned for its own ground-based ASAT system, the kinetic-energy ASAT (KE-ASAT) program. The program was terminated in 1993, restarted in 1996, and continued until 2001. The KE-ASAT system was never tested on a space-based object
Early 2000s	Satellite jamming—interfering with radio communications between a satellite and a ground system—was developed as an ASAT technology. In 2002, the US unilaterally withdrew from the ABM treaty, refocusing space efforts. The US deployed a satellite jamming system, ground-based midcourse missile defense interceptors, and proposed the testing of space-based missile defense
2005–2007	China began testing the SC-19 system, a direct ascent ASAT system armed with a kinetic kill vehicle (KKV) using an infrared seeker to identify and track its target of low Earth orbit satellites. During a SC-19 test in 2007, China deliberately hit and destroyed one of its own defunct weather satellites, creating more than thousands of trackable space debris fragments
2008	The ASAT capabilities of the US sea-based Aegis missile defense interceptors was tested by destroying a non-working US satellite at an altitude of about 150 miles
2010	China conducted a test of ground-based midcourse missile system against a ground-launched ballistic missile target, an event confirmed by the US military. India announced its intentions to develop a hit-to-kill ASAT system
Current Day	Chinese ASAT systems remain secret, but it is thought that it has ASAT capability to geosynchronous orbit Russia has been testing a new anti-satellite missile system known as PL19/Nudol, a direct ascent anti-satellite weapon. The Nudol is part of a myriad of new technology kinetic interceptor systems being developed The US also continues to develop and test systems that progress ASAT technology and abilities

Anti-Ballistic Missile (ABM) Treaty (1972–2002)

A treaty between the US and Soviet Union that restricted the number of defensive antiballistic missile (ABM) systems for both nations, with the aim and effect of deescalating the nuclear arms race. The treaty limited each country to two ABM sites—one would protect an ICBM silo and the second would protect the national capital. The treaty was signed by US President Richard Nixon and Soviet leader Leonid Brezhnev in 1972. However, President Ronald Reagan's promotion of his Strategic Defense Initiative (SDI) during the 1980s launched a new stage of the arms race. In 2001, President George W. Bush stated that the US would formally withdraw from the ABM Treaty, expressing concern over the imposed restrictions and supporting further development of defenses against possible enemy or terrorist ballistic missile attacks. The withdrawal took effect in 2002.³

Ballistic Missile Defense System (BMDS)

A layered defense system built for the US and its allies to defend against ballistic missile attacks in all phases of flight and in multiple ranges. The system “detects, tracks, intercepts, and destroys incoming ballistic missiles and/or their warhead payloads. A fully operational defense consists of sensors to detect a missile launch and to track the missile and warhead; interceptors to disable or destroy the missile or warhead; and a command and control system.”⁴

BMDS's can be deployed from the ground, air, sea, or in space. They can destroy missiles and their payloads during all three stages of the flight—boost, midcourse, and terminal phase.

Historical Context

The following information was taken from official, unclassified Department of Defense documents and highlights the aims and scope of the more recent US missile defense agenda.

“Following guidance from the President, the Secretary of Defense approved the Ballistic Missile Defense (BMD) Review Report (dated February 2010), which established the following policy priorities to frame missile defense development and acquisition program strategies:

³Arms Control Association. [Internet]. armscontrol.org. The Anti-Ballistic Missile (ABM) Treaty at a Glance. 2012. [cited 2018 Jul 25]. Available from: <https://www.armscontrol.org/factsheets/abmtreaty>

⁴IFPA. [Internet]. ifpa.org. Missile Defense, the Space Relationship, and the Twenty-First Century. 2009. [cited 2018 Jul 27]. Available from: <http://www.ifpa.org/pdf/FAQ-bmd.pdf>

1. The U.S. will continue to defend the homeland against the threat of limited ballistic missile attack.
2. The U.S. will defend against regional missile threats to U.S. forces, while protecting allies and partners and enabling them to defend themselves.
3. Before new capabilities are deployed, they must undergo testing that enables assessment under realistic operational conditions.
4. The commitment to new capabilities must be fiscally sustainable over the long term.
5. U.S. BMD capabilities must be flexible enough to adapt as threats change.
6. The U.S. will seek to lead expanded international efforts for missile defense.”⁵

Ballistic Missile Early Warning System (BMEWS)

In 1959, this became the first operational missile detection radar. Via stations built in the northern hemisphere, the BMEWS could provide immediate long-range warning of a missile attack over the polar region.⁶

Historical Context

With the growing threat posed by Soviet ICBMs in the last years of the 1950s, the ability to receive advance warning of a missile attack was given high priority. The BMEWS was designed to assist with warning of a missile attack. The system employs phased array antenna technology, which aims the antenna and steers the beam. This process takes place in millionths of a second by electronically controlling the incoming and outgoing signals. The BMEWS is able to detect and track multiple targets, an important capability for a massive missile attack. The system must be able to locate and distinguish vehicle types, and also analyze trajectories and targets.

The following timeline is taken with permission from the Union of Concerned Scientists.⁷

⁵Ballistic Missile Defense System. Selected Acquisition Report. 2017. c2018. [Internet]. [cited 2018 May 26]. Available from: <http://www.dtic.mil/dtic/tr/fulltext/u2/1018994.pdf>

⁶<https://www.globalsecurity.org/space/systems/bmews.htm>

⁷Union of Concerned Scientists. [Internet]. *A History of Anti-Satellite Programs* (2012); Feb 2012. [cited 2018 Aug 14]. Available from: <https://www.ucsusa.org/nuclear-weapons/space-security/a-history-of-anti-satellite-programs#.W3M6Gc4zq70>

Table C.2 History of Ballistic Missile Early Warning System (BMEWS)

1958	Approval was given by the Air Force for the construction of the Ballistic Missile Early Warning System (BMEWS). The total system consisted of three radar installations including data computational facilities in North American Aerospace Defense Command (NORAD) headquarters
By the mid-1960s	BMEWS radars were activated in Greenland, Alaska, and England. These radars were able to detect an incoming ICBM attack with 15 minutes warning and provide tracking data on most orbiting satellites. The Air Force still supports the three BMEWS Radars. The satellite tracking data is sent to the Joint Space Operations Center (JSpOC) for processing

Boost Surveillance and Tracking System (BSTS)

One component of the SDI layered defense system that focused on sensor detection of a missile launch with the capability to track and give warning of a rocket’s trajectory.

Historical Context

The Satellite Defense Initiative (SDI) was designed to be a multilayer defense against a massive Soviet ballistic missile attack. The boost and post-boost ballistic missile phases required an advanced missile warning system to detect launches and maintain accurate tracking. The result was the high-altitude Boost Surveillance and Track System (BSTS), which used large optics and unparalleled levels of signal and data processing. A constellation of several satellites in high orbit was proposed. At high altitudes, the optical resolution might be inadequate, so it was thought that lower altitude sensors might be needed to achieve the required accuracy.

It was claimed that deployment of the BSTS (planned originally for 1995) could provide improved early warning of a missile attack, along with enhanced intelligence collection. In 1990, the Space-Based Interceptor was replaced with Brilliant Pebbles, dropping the Boost Surveillance and Tracking System. The Air Force took over management of BSTS to improve upon and replace the existing DSP system. BSTS was renamed the Advanced Warning System (AWS) and later on the Follow-on Early Warning System (FEWS).⁸

⁸Global [Security.org](https://www.globalsecurity.org/space/systems/bsts.htm). [Internet]. c2018. Boost Surveillance and Tracking System (BSTS). [cited 2018 May 26]. Available from: <https://www.globalsecurity.org/space/systems/bsts.htm>

Brilliant Pebbles (BP)

A space-based, kinetic kill interceptor that was designed to be part of the Strategic Defense Initiative (SDI) program.

Historical Context

Brilliant Pebbles became a central component of the SDI program during its brief lifespan. In 1990, the Strategic Defense Initiative Organization (SDIO) decided to pursue the concept as an alternative weapons option. The system consisted of a system of highly individual interceptors floating independently in orbit. BP interceptors were designed to destroy Soviet ICBMs during their boost phase. A single Brilliant Pebbles interceptor could destroy as many as ten Soviet warheads from their Earth orbits.

Brilliant Pebbles replaced the Space-Based Kinetic Kill Vehicles of the original SDI architecture, which were susceptible to Soviet anti-satellite weapons and were heavy and expensive. The planned BP concept consisted of smaller, individual, and more numerous space-based interceptors that could be mass produced to lower overall costs.⁹

The following timeline is taken with permission from the Union of Concerned Scientists.

Table C.3 History of Brilliant Pebbles

1989	The Strategic Defense Initiative Organization (SDIO) made the decision to pursue the Brilliant Pebble concept, which could significantly reduce the costs of SDS Phase I
1990	Flight testing began in 1990, with completion scheduled for 1993. Due to problems before the first test flight, the test schedule was delayed by several months
1992	By this time, successful advancements had been made in SDI technology. Despite this success, President Reagan and his SDI program became a target of deep criticism from political adversaries
1993	The Brilliant Pebbles program was scaled back and finally terminated. Thereafter, efforts shifted from defense against strategic missiles toward defense against theater ballistic missiles launched by rogue nations. A Boost Phase Interceptor (BPI) concept was approved to address this new threat

Defense Support Program (DSP)

Defense Support Program (DSP) satellites deliver early warnings for Intercontinental Ballistic Missiles (ICBM) and tactical launches. They are operated by the Air Force Space Command and form a crucial part of early warning

⁹Missile Defense Agency. c2018. [Internet]. The Rise and Fall of Brilliant Pebbles. [cited 2018 May 26]. Available from: <http://highfrontier.org/wp-content/uploads/2012/09/The-Rise-and-Fall-of-Brilliant-Pebbles-Baucom.pdf>

systems in the US. Utilizing infrared sensors to detect heat from missile and booster plumes against the Earth's background, DSP satellites are capable of identifying missile and space launches as well as nuclear detections. They travel in 22,300-mile geosynchronous orbits.

Historical Context

When they were first launched in 1970, DSP satellite remained classified. Over the span of 37 years, a total of 23 DSP satellites were launched into orbit. Since the 1970s, DSP satellites have provided a consistent early warning network.

In 1995, technological advancements improved the capabilities of DSP satellites, allowing them to provide even more precise and reliable data to track evolving missile threats. As detailed by the Air Force Space Command:

On-station sensor reliability has provided uninterrupted service well past their design lifetime. Recent technological improvements in sensor design include above-the-horizon capability for full hemispheric coverage and improved resolution. Increased on-board signal-processing capability improves clutter rejection. Enhanced reliability and survivability improvements were also incorporated. The Space Based Infrared System is projected to replace DSP.¹⁰

The capabilities of DSP satellites were demonstrated effectively during Operation Desert Storm.¹¹

Exoatmospheric Kill Vehicle (EKV)

A US weapon that can be employed against long-range ballistic missiles. The kinetic-force weapon works by destroying such missiles while they are still in space. The EKV is the intercept component of the Ground-Based Interceptor and part of the Ground-based Midcourse Defense System.¹²

¹⁰ Defense Support Program Satellites. [Internet]. c2018. U.S. Air Force Fact Sheet. 2003 March. [cited 2018 May 26]. Available from: <http://space.au.af.mil/factsheets/dsp.htm>

¹¹ Defense Support Program Satellites. [Internet]. c2018. U.S. Air Force Fact Sheet. 2003 March. [cited 2018 May 26]. Available from: <http://space.au.af.mil/factsheets/dsp.htm>

¹² Raytheon Fact Sheet. [Internet]. c2018. Kill Vehicles: First line of defense against ballistic missiles. [cited 2018 Jul 26]. Available from: <https://www.raytheon.com/capabilities/products/ekv>

Historical Context

In the late 1990s, the Department of Defense awarded a contract to Raytheon to develop Exoatmospheric Kill Vehicles. The early test results proved less than expected, however, the most recent EKV advances have improved the chances of intercept. Future versions of EKV include the Redesigned Kill Vehicle (RKV), which is expected to lower overall costs and improve maintainability and reliability. The new EKV generations will feature a modular design. Additionally, Raytheon is working on a Multi-Object Kill Vehicle (MOKV), which can intercept several objects in space. In May 2017, the system successfully intercepted an intercontinental ballistic missile, destroying its target over the Pacific Ocean.¹³

Ground-Based Mid-course Defense (GMD)

An element of the Ballistic Missile Defense System that provides the capability to engage and destroy intermediate- and long-range ballistic missile threats in space. The system consists of interceptors and their associated ground support systems. The Ground-Based Interceptor is a multi-stage rocket that carries an Exoatmospheric Kill Vehicle (EKV). Guided by precise data, the booster takes the EKV towards the target. The EKV uses kinetic force via a direct collision to destroy the warhead. The impact occurs outside the Earth's atmosphere, in space. The hit-to-kill technology has been successfully tested, three using Ground-Based Interceptors.¹⁴

Joint Space Operations Center (JSpOC)

A command and control weapons system that detects, tracks, and identifies all artificial objects in Earth orbit. It carries out the US Strategic Command's Joint Functional Component Command for Space (JFCC SPACE) mission and serves as a center for worldwide joint space forces.¹⁵ It performs all of the orbit determination activity necessary to maintain the US space catalogue, collecting and analyz-

¹³Global Security.org. [Internet]. c2018. GBI Exoatmospheric Kill Vehicle. [cited 2018 May 26]. Available from: <https://www.globalsecurity.org/space/systems/gbi-ekv.htm>

¹⁴U.S. Department of Defense. [Internet]. Ground Based Missile Defense; [cited 2018 May 24]. Available from: <https://www.mda.mil/system/gmd.html>; <https://www.mda.mil/system/gmd.html>

¹⁵Fact Sheet. [Internet]. Joint Functional Component Command for Space. 15 Mar 2013. [cited 2018 Jul 24]. Available from: <https://www.vandenberg.af.mil/About-Us/Fact-Sheets/Display/Article/338339/joint-functional-component-command-for-space/>

ing data from various sources to aid this effort and establish a more comprehensive view of Earth-orbiting spacecraft.¹⁶ The center is located at Vandenberg Air Force Base in California.

The Landsat (Earth Resources Technology Satellite) Program

A series of Earth-observing satellite missions jointly managed by NASA and the US Geological Survey.

Historical Context

The Earth Resources Technology Satellite (ERTS-1), later renamed Landsat 1, was launched by the US in 1972. Additional Landsat satellites followed in the 1970s and 1980s. At present, both Landsat 7 and 8 are in orbit and collecting data. Landsat 9 is currently being developed, with a launch scheduled for late 2020.¹⁷

Missile Defense Alarm System (MIDAS)

Managed by the US military, it was a system of early warning satellites that were launched from 1960 to 1966. MIDAS was the predecessor of the Integrated Missile Early Warning Satellite (IMEWS) program. The satellites were designed to use infrared sensors that could detect ballistic missile launches from low Earth orbit.

Historical Context

Launched in 1960, the first MIDAS satellite failed to reach orbit. MIDAS 2, launched shortly after, became the first infrared reconnaissance satellite in space. However, after only 2 days, its telemetry system failed. MIDAS 3 was successfully launched in mid-1961 and reached its orbit; at the time, it was the heaviest

¹⁶US Strategic Command. [Internet]. Combined Space Operations Center established at Vandenberg AFB. 19 Jul 2018. [cited 2018 Jul 26]. Available from: <http://www.stratcom.mil/Media/News/News-Article-View/Article/1579497/combined-space-operations-center-established-at-vandenberg-afb/>

¹⁷USGS. [Internet]. What is the Landsat satellite program and when did it begin? C2018. [cited 2018 Jul 24]. Available from: <http://www.stratcom.mil/Media/News/News-Article-View/Article/1579497/combined-space-operations-center-established-at-vandenberg-afb/>

American satellite. Over the program's lifespan, a total of 12 MIDAS satellites were launched. The 12 spacecraft employed four different types of increasingly advanced sensors, setting the stage for the successor program, IMEWS.¹⁸

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 treaty entered into force in 1967 and has remained the foundation for international space law. It is aimed at the peaceful use of outer space, employing general language that allows it to adapt to developments in the space industry.

According to the United Nations Office for Outer Space Affairs (UNOOSA), the treaty outlines the following principles:¹⁹

- the exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all mankind;
- outer space shall be free for exploration and use by all States;
- outer space is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means;
- States shall not place nuclear weapons or other weapons of mass destruction in orbit or on celestial bodies or station them in outer space in any other manner;
- the Moon and other celestial bodies shall be used exclusively for peaceful purposes;
- astronauts shall be regarded as the envoys of mankind;
- States shall be responsible for national space activities whether carried out by governmental or non-governmental activities;
- States shall be liable for damage caused by their space objects; and
- States shall avoid harmful contamination of space and celestial bodies.
- Ninety-eight States have ratified, and an additional twenty-seven have signed the Outer Space Treaty as of January 1, 2008.

The complete treaty is shown in Appendix A.

¹⁸Encyclopedia of Defense Systems. [Internet]. MIDAS. Missile Defense Alarm System; [cited 2018 Jun 24]. Available from: <http://www.daviddarling.info/encyclopedia/M/MIDAS.html>

¹⁹United Nations Office for Outer Space Affairs. [Internet]. c2018. Intro Outer Space Treaty [cited 2018 Jul 26]. Available from: <http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html>

Space-Based Infrared System (SBIRS)

An early warning defense satellite system being developed by Lockheed Martin for the US Air Force Space Command (AFSPC). The system is comprised of a constellation of GEO satellites, HEO payloads, and ground processing control systems. The SBIRS aims to deliver long-range surveillance and accurate detection capabilities that will significantly strengthen US missile defense efforts and warning technology. The system will be able to sense and transmit infrared data for multiple targets at once. The SBIRS will replace the US Air Force's DSP early warning system.²⁰

Historical Context

The US Department of defense initiated the SBIRS in 1996. Originally, the system was designed to incorporate high- and low-orbiting space-based satellites, along with ground processing equipment. In 2001, SBIRS was transferred to the Missile Defense Agency and rebranded as the Space Tracking and Surveillance System (STSS). SBIRS High was certified for operations later that same year and now bears the name of the original program, simply SBIRS.

The SBIRS was initiated by the US Department of Defense (DoD) in 1996 and was initially planned to include high and low orbiting space-based and ground processing equipment. The DoD transferred SBIRS Low to the Missile Defense Agency and renamed it as the space tracking and surveillance system (STSS) in 2001, while SBIRS High was certified for operations in December 2001 and is now known simply as SBIRS.²¹

The Space Resource Exploration and Utilization Act

Also known as the Space Act, this 2015 Act changed existing commercial space policy and set up new guidelines for emerging US commercial spaceflight. The Act granted property rights to US companies mining asteroid resources: "A U.S. citizen involved in commercial recovery of asteroid resources will be entitled to

²⁰ Air Force Technology. [Internet]. Space Based Infrared System (SBIRS); [cited 2018 May 24]. Available from: <https://www.airforce-technology.com/projects/space-based-infrared-system-sbirs/>

²¹ Air Force Technology. [Internet]. Space Based Infrared System (SBIRS); [cited 2018 May 24]. Available from: <https://www.airforce-technology.com/projects/space-based-infrared-system-sbirs/>

‘possess, own, transport, use and sell’” the materials thus extracted, subject at all times to the international obligations of the United States. The Act aimed to incentivize the development of the US commercial space industry, fostering both competitiveness and entrepreneurship.²²

Space Tracking and Surveillance System (STSS)

A low Earth orbit ballistic missile defense system that tracks missiles through all three phases of flight—boost, midcourse, and terminal. STSS can differentiate between warheads and decoys. Its sensor data is transmitted to other systems, cueing radar and providing precise intercept handover data that allows missile defense interceptors to hit and disable or destroy their targets.²³

Historical Context

In September 2009, the Missile Defense Agency (MDA), NASA, and the Air Force launched the first two satellites of the STSS-D constellation. Stationed in low Earth orbit at around 839 miles, the satellites are controlled by the Missile Defense Space Development Center (MDSDC). They completed an early test series in 2010.

Although the STSS-D satellites deliver accurate coverage and tracking of missile launches, roughly 30 satellites are required to provide coverage around the entire globe. STSS-D satellites were designed with a 2-year lifespan, in the belief that they would be used only as demonstration satellites. This lifespan has already been exceeded; at present, there are no new plans in place to launch additional satellites.

In 2015, Northrop Grumman Aerospace, a defense contractor, was given a contract to provide on-orbit operations and maintenance duties for the STSS program.²⁴

²² [Congress.gov](https://www.congress.gov/bills/114/congress-house-bill/2262/text). [Internet]. c2018. H.R.2262—U.S. commercial space launch competitiveness act; [cited 2018 May 24]. Available from: <https://www.congress.gov/bill/114th-congress/house-bill/2262/text>

²³ CSIS Missile Defense Project. [Internet]. c2018. Space Tracking and Surveillance System; [cited 2018 Jun 24]. Available from: <https://missilethreat.csis.org/defsyst/ss/>

²⁴ Missile Defense Advocacy. [Internet]. Space Tracking and Surveillance System (STSS). 2016 Feb. [cited 2018 May 24]. Available from: <http://missiledefenseadvocacy.org/missile-defense-systems-2/missile-defense-systems/u-s-deployed-sensor-systems/space-tracking-and-surveillance-system/>

The Strategic Defense Initiative (SDI)

A Reagan-era missile defense system designed to protect the US from Soviet intercontinental ballistic missiles (ICBMs) and potential nuclear attacks. The system would intercept such missiles at the different stages of their flight. In order to be effective against targets moving at such high velocities, the system needed to employ highly advanced technology that had yet to be researched or developed at the time.

The proposed designs for such a defense system included both space- and earth-based laser battle stations. Extremely sensitive radar, infrared, and optical sensors could be based on the ground, in the air, and in space.

Historical Context

Known popularly as “Star Wars” after the franchise of the same name, this initiative was introduced by President Ronald Reagan in a televised address on March 23, 1983.

The program was criticized for its technological uncertainties in addition to its enormous cost. Although work on the program did begin, the technological research required to reach its goals was too intensive and costly to reap any immediate rewards. A large portion of the program’s budget was cancelled by later administrations. The idea behind this missile defense system influenced the later development of the National Missile Defense.²⁵

Tracking and Data Relay Satellite (TDRS)

Begun in the early 1970s, this satellite system makes up the space segment of the Space Network. TDRS spacecraft form effective communication links between ground stations and orbiting satellites. Currently, the TDRS satellite configuration is composed of ten in-orbit satellites, which are distributed in around the Earth in a formation that provides the reliable, nearly uninterrupted relaying of information.²⁶ The TDRS satellites are managed by NASA’s Goddard Space Flight Center.

²⁵ U.S. Department of Defense. [Internet]. Ground Based Missile Defense; [cited 2018 May 24]. Available from: <https://www.congress.gov/bill/114th-congress/house-bill/2262/text>; <https://www.mda.mil/system/gmd.html>

²⁶ NASA.gov. [Internet]. Tracking and Data Relay Satellite (TDRS); 07 Sept 2017. [cited 2018 May 24]. Available from: https://www.nasa.gov/directorates/heo/scan/services/networks/tdrs_main

Appendix D: Timeline of Missile Defense

The following timeline up to January 2002 is taken with permission from:

<http://www.atomcentral.com/missile-defense.aspx>.

The timeline from March 2002 onward is taken with permission from:

<https://www.ucsusa.org/nuclear-weapons/us-missile-defense/missile-defense-timeline#bf-toc-2>

Table D.1 A timeline of missile defense

The 1940s	
8 September 1944	First German V-2 missile struck London
1945/1946	Following World War II, the US learned of Nazi plans for an ICBM that could have reached New York City by 1946
4 July 1945	A delegation of American officers that investigated the use of ballistic missiles during World War II recommended a research and development program to develop defenses against these new weapons
December 1945	A report by the Scientific Advisory Group of the US Army Air Forces considered the use of missiles and a form of energy beam to defend against missile attacks
4 March 1946	The Army Air Forces initiated two long-term studies, Projects Thumper and Wizard. These studies explored the use of interceptor missiles to destroy missiles travelling as fast as 4000 mph at an altitude as high as 500,000 ft

(continued)

Table D.1 (continued)

29 May 1946	The Stilwell Board Report recommended the development of defenses against ballistic missiles. “Guided missiles, winged or nonwinged, traveling at extreme altitudes and at velocities in excess of supersonic speed, are inevitable. Intercontinental ranges of over 3000 miles and payload[s] sufficient to carry atomic explosive[s] are to be expected. Remotely controlled, and equipped with homing devices designed to be attracted to sound, metal, or heat, such missiles would be incapable of interception with any existing equipment such as fighter aircraft and antiaircraft fire. Guided interceptor missiles, dispatched in accordance with electronically computed data obtained from radar detection stations, will be required”
The 1950s	
September 1953	Seven marshals who had led Soviet efforts in World War II asked the Central Committee of the Communist Party of the Soviet Union to investigate the possible development of an ABM system. The study determined that missile defenses were possible. This led the Soviets to initiate their ABM development program at the end of 1953
1955	Using an analog computer, Bell Telephone Laboratories completed 50,000 simulated intercepts of ballistic missile targets. These simulations indicated that it was possible to hit a missile with another missile
16 January 1958	The US Army was assigned primary responsibility for the ballistic missile defense mission, making the Air Force scale back its ongoing research and making the radar and command and control equipment compatible with the Army’s Nike Zeus ballistic missile defense system
The 1960s	
4 March 1961	The Soviets were reported to complete their first interception and destruction of a missile warhead. An official report described the Soviet first interception as follows: “The V-1000 antimissile was launched according to a computer command. The detonation of the antimissile’s high-explosive fragmentation warhead was conducted at an altitude of 25 km according to a command from Earth from a computer after which, based upon data from the film recorder, the ballistic missile warhead began to fall apart”
19 July 1962	A Nike Zeus missile fired from the Army’s Kwajalein test facility intercepted a dummy warhead from an Atlas ICBM
22 December 1962	A Zeus missile came within 200 m of a reentry vehicle during a simulated intercept over the Pacific Ocean
10 November 1966	Secretary of Defense Robert S. McNamara informed the American people that the Soviets were deploying their Galosh ballistic missile defense system
23 June 1967	At the Glassboro summit, President Lyndon Johnson and Secretary of Defense Robert McNamara stated that the Soviets should abandon their effort to deploy missile defenses, because the US could just add more nuclear warheads to its ICBM force to overcome these defenses. The following response came from Kosygin: “Defense is moral; offense is immoral!”

(continued)

Table D.1 (continued)

18 September 1967	Secretary of Defense Robert S. McNamara announced President Lyndon Johnson's decision to deploy the Sentinel ballistic missile defense system. The system was designed to protect the US from the so-called "Nth country threat," an attack by unsophisticated ICBMs such as those built by the People's Republic of China
6 February 1969	Secretary of Defense Melvin Laird halted the deployment of the Sentinel system pending the completion of a review of US strategic programs by the new administration of President Richard Nixon
14 March 1969	President Richard Nixon announced his decision to deploy a missile defense system essentially designed to protect US ICBM fields from attack by Soviet missiles. The reoriented missile defense system was renamed Safeguard
The 1970s	
26 May 1972	US President Richard Nixon and Soviet General Secretary Leonid Brezhnev signed the SALT I agreements (including the ABM Treaty). This treaty limited both countries to the deployment of two ABM sites, each having 100 interceptors
1976	In view of technical limitations and the restrictions stated in the ABM Treaty, Congress ordered the Army to close down the Safeguard system. The Soviets continued to maintain their own ABM system near Moscow
The 1980s	
6 January 1984	Presidential National Security Decision Directive 119 established the Strategic Defense Initiative (SDI) to explore the possibility of developing missile defenses as an alternative means of deterring nuclear war
10 June 1984	The core of the Army's new hit-to-kill interceptor technology was successfully demonstrated in the homing overlay experiment, where a test intercept vehicle was launched from Kwajalein Missile Range aboard a modified Minuteman rocket
14 June 1989	President Bush stated that the goals of the SDI program were generally sound and that the program should continue in order to offer the possibility of a deployment decision in the next few years
Summer 1989	Four major studies of the Brilliant Pebbles concept carried out concluded that Brilliant Pebbles was a promising, technically feasible concept
The 1990s	
18 January 1991	Press reports stated that for the first time in history, an anti-missile missile intercepted and destroyed a ballistic missile under combat conditions (a Patriot air defense missile destroyed an Iraqi Scud missile)

(continued)

Table D.1 (continued)

28 April 1991–6 May 1991	On 28 April, the space shuttle Discovery blasted off from Cape Canaveral with several major SDIO experiments aboard. One of the experiments carried out on this mission was the shuttle's execution of a maneuver known as the "Malarkey Milkshake" maneuver, where the shuttle's engines fired 17 times. This maneuver was part of an experiment that observed the firing of the shuttle's engines against various backgrounds, e.g., against the earth, against black space, etc. The shuttle mission ended on 6 May when the Discovery landed at Cape Canaveral
13 May 1993	Secretary of Defense Les Aspin announced that the Strategic Defense Initiative Organization was being renamed the Ballistic Missile Defense Organization because of its new focus in DOD's missile defense program
30 November 1993	The Extended Range Interceptor (ERINT) was successfully tested at the White Sands Missile Range in New Mexico. The ERINT collided with the warhead of a STORM target vehicle
16 February 1994	An Extended Range Interceptor (ERINT) destroyed a ballistic missile in a test conducted at the White Sands Missile Range in New Mexico
11 May 1994	A Scud missile struck the North Yemen city of Sanaa
Mar 1996	The Peoples' Republic of China (PRC) fired four M-9 missiles that landed in the vicinity of Taiwan
24 January 1997	A modified Standard Missile 2 Block IVA successfully intercepted and destroyed a Lance missile target at the White Sands Missile Range. This was the first successful intercept of a missile by the SM2
7 February 1997	BMDO and the US Army's Space and Strategic Defense Command carried out a test of a Patriot Advanced Capability-2 (PAC-2) missile, which intercepted a theater ballistic target missile
24 June 1997	BMDO's Joint Program Office, in conjunction with the US Army's National Missile Defense Program Office and the Air Force's 30th Space Wing, completed the first flight test (IFT-1A) of "a candidate infrared sensor designed for possible use with the National Missile Defense (NMD) program"
19 August 1997	The fifth flight of the Arrow 2 anti-tactical ballistic missile veered off course soon after launch and had to be destroyed for range safety purposes
26 September 1997	The Navy conducted a risk reduction missile flight test at the Pacific Missile Range Facility (PMRF) in Kauai, HI, using a modified SM-2 Block IV. The missile did not enter the upper atmosphere and thus did not achieve the conditions that were prerequisite for the primary test objective
17 October 1997	The US Army test-fired the Mid-Infrared Advanced Chemical Laser (MIRACL) at a satellite. Neither the satellite's laser camera nor the satellite was damaged in the test
15 December 1997	The second PATRIOT Advanced Capability (PAC)-3 missile executed a pull up maneuver using 14 attitude control motors. The missile flight was nominal

(continued)

Table D.1 (continued)

15 January 1998	The National Missile Defense (NMD) Integrated Test Flight-2 (IFT-2) was carried out successfully
14 April 1998	The Kraken cruise missile crashed on takeoff from Point Mugu, California
17 April 1998	The Ballistic Missile Defense Organization (BMDO) announced the successful launch of its Red Crow Flight Experiment, which assessed the operational performance of a suite of ballistic missile countermeasures
12 May 1998	THAAD (Theater High Altitude Area Defense) Flight Test 08 was conducted at White Sands Missile Range, New Mexico at 05:22 Mountain Standard Time. The test was a failure. Preliminary investigation indicated that the THAAD missile lost control shortly after launch. The missile impacted on the White Sands Missile Range about two miles north of the launch site. The cause of the failure was later determined to be an electronic short affecting the missile's thrust-vector control system. This was the fifth straight failure to intercept for THAAD. The previous fourth failure had triggered major concern about the program
15 July 1998	The Commission to Assess the Ballistic Missile Threat to the United States (Rumsfeld Commission) was unanimous in its conclusion: "Concerted efforts by a number of overtly or potentially hostile nations to acquire ballistic missiles with biological or nuclear payloads pose a growing threat to the United States, its deployed forces and its friends and allies. These newer, developing threats in North Korea, Iran and Iraq are in addition to those still posed by the existing ballistic missile arsenals of Russia and China, nations with which we are not now in conflict but which remain in uncertain transitions. The newer ballistic missile-equipped nations' capabilities will not match those of US systems for accuracy or reliability. However, they would be able to inflict major destruction on the US within about 5 years of a decision to acquire such a capability (10 years in the case of Iraq). During several of those years, the US might not be aware that such a decision had been made"
21 July 1998	Iran carried out the first flight test of its Shahab-3 medium-range ballistic missile
31 August 1998	North Korea flight tested its Taepo Dong-1 missile in a flight that traveled about 1000 mi over Japan
10 February 1999	The National Missile Defense program conducted Risk Reduction Flight 5, which demonstrated real time element hardware and software capabilities and system interfaces
15 March 1999	BMDO and the US Army successfully conducted the Patriot Advanced Capability-3 missile Seeker Characterization Flight (SCF) test at White Sands Missile Range, NM. In addition, the PAC-3 missile intercepted the Hera target missile
29 March 1999	For a sixth time, in a flight test at White Sands Missile Range, THAAD failed to hit its target
11 April 1999	India successfully tested its Agni II missile

(continued)

Table D.1 (continued)

14 April 1999	Pakistan carried out a test of its Ghauri II missile just 3 days after India conducted a test of its Agni II missile
15 April 1999	Pakistan test-fired its 450-mile Shaheen missile
25 May 1999	The THAAD missile test (10th in a series of 13 tests) was aborted when the Hera target missile failed to follow the appropriate trajectory
3 June 1999	Russia conducted another successful test of its Topol M missile
10 June 1999	THAAD successfully intercepted a Hera target missile at White Sands Missile Range
2 August 1999	The 11th flight test for the THAAD system was successfully completed when the THAAD interceptor struck a Hera target missile outside the Earth's atmosphere
16 Sep 99	The Ballistic Missile Defense Organization and the US Army today conducted a successful intercept test of the PATRIOT Advanced Capability-3 (PAC-3) missile at the White Sands Missile Range, N.M., showing the capability of the ground system and missile to detect, track, and engage the target, and to collect data to evaluate missile homing functions
2 Oct 99	BMDO and the US Army Space and Missile Defense Command successfully launched a modified Minuteman intercontinental ballistic missile (ICBM) target vehicle from Vandenberg AFB, California; a prototype NMD interceptor launched approximately 20 min later and 4300 mi away from the Kwajalein Atoll in the Republic of the Marshall Islands. The intercept demonstrated the ability of the exoatmospheric kill vehicle to intercept and destroy a ballistic missile target outside the atmosphere
1 Nov 99	The Arrow II missile system successfully completed its first fully integrated intercept test where the Arrow took off and flew in a nominal trajectory, acquired the TM-91 target, then locked on and homed in on the target missile
The 2000s	
18 January 2000	During NMD's IFT-4 flight test, the interceptor failed to hit its target
5 February 2000	A PAC-3 missile successfully intercepted its Hera target over the deserts at White Sands Missile Range
15 March 2000	A PAC-2 production missile was fired by the Army from a PAC-3 launcher and "successfully engaged" a target that was towed behind a MQM-107 drone
8 July 2000	The IFT-5 test, a major test in the US National Missile Defense program, failed to achieve the planned intercept
14 October 2000	The Ballistic Missile Defense Organization and the US Army completed a complex test involving three targets and two interceptor missiles. The test entailed a simultaneous engagement using a PAC-3 and a PAC-2 missile and two targets, one a ballistic missile, the other an air-breathing drone
25 January 2001	BMDO and the US Navy conducted a successful flight test of newly developed Standard Missile-3 (SM-3)

(continued)

Table D.1 (continued)

June 2001	The Defense Science Board Task Force on High Energy Laser Weapon Systems Applications completed its study concluding that “high-power lasers” had “the potential to change future military operations in dramatic ways”
14 July 2001	The BMDO’s Mid-Course Joint Program Office, and the US Army successfully completed an integrated test of BMDO’s mid-course, exoatmospheric kinetic kill vehicle
31 August 2001	BMDO launched a missile from Vandenberg Air Force Base, California. All three stages of the booster operated properly. BMDO considered the test successful
3 December 2001	BMDO and the US Army successfully completed Integrated Flight Test 7 (IFT-7) in the Ground-Based Midcourse segment portion of the overall missile defense program
13 December 2001	During the Boost Vehicle Three (BV-3) test, the prototype booster for the Ground-Based Midcourse segment of the Ballistic Missile Defense System in the Boost Vehicle Three (BV-3) drifted off course and had to be destroyed for range safety reasons after only about 30 sec of flight
02 January 2002	Secretary of Defense Donald Rumsfeld issued guidance on the execution of the US missile defense program. Included was the renaming of the Ballistic Missile Defense Organization to the Missile Defense Agency
15 March 2002	Successful intercept test (IFT-8) of the Ground-Based Midcourse system included three balloon decoys (one large and two small)
June 2002	Ground broken at Fort Greely, Alaska for construction of six missile interceptor silos as a test bed for missile defense system
17 December 2002	President Bush announced that he had instructed the Secretary of Defense to begin fielding a ground-based missile defense that would achieve initial operational capabilities in 2004
14 October 2002	This successful intercept test (IFT-9) of the Ground-Based Midcourse system used the same decoys as the previous test, but a modified warhead. The ship-based SPY-1 radar observed the test for the first time, assessing the radar’s capacity to track long-range missiles
11 December 2002	This intercept test (IFT-10) of the Ground-Based Midcourse system was unsuccessful because the exoatmospheric kill vehicle (EKV) failed to separate from the interceptor and the booster rocket (the same failure as IFT-5 on July 8, 2000, detailed above). This was the first IFT performed at night. Previous tests were conducted earlier in the day, with the Sun illuminating the targets from behind the kill vehicle
22 July 2004	First interceptor installed in silo at Fort Greely, Alaska
15 December 2004	This intercept test (IFT-13C) of the Ground-Based Midcourse system failed when the booster carrying the interceptor failed to leave the ground in a launch from Kwajalein atoll. The interceptor was to hit a target coming out of Kodiak, Alaska
13 February 2005	This intercept test (IFT-14) was a repeat of the test on December 15, 2004, and the interceptor again failed to leave the silo

(continued)

Table D.1 (continued)

1 September 2006	Intercept test (FTG-2) of the Ground-Based Midcourse system. The target ballistic missile was successfully intercepted over the Pacific, having been launched from the Kodiak Launch Complex in Alaska. The interceptor was launched from Vandenburg Air Force Base. No decoys were used
21 March 2007	The target vehicle in this test was successfully tracked by the Sea-Based X-band (SBX) radar and two Aegis Ballistic Missile Defense ships using onboard SPY-1 radar
25 May 2007	The interceptor for a test (FTG-3) of the Ground-Based Midcourse system at Vandenburg Air Force Base was aborted because the target vehicle launched from Kodiak, Alaska, fell far short of the designated interceptor range in the Pacific
28 September 2007	Repeat (FTG-3A) of the May 25, 2007 intercept test of the Ground-Based Midcourse system. A target missile launched from Kodiak, Alaska was successfully intercepted by an interceptor launched from Vandenberg Air Force Base
18 July 2008	Test of the Ground-Based Midcourse system initially planned as an intercept attempt. Faulty parts in the test interceptor made the Missile Defense Agency (MDA) officials focus on the performance of four sensors to track a test target: the Sea-based X-band radar, the AN/TPY-2 X-band radar, the Aegis Long-Range Surveillance and Track system, and an upgraded early warning radar in Beale Air Force Base, California
5 December 2008	Intercept test (FTG-5) of the Ground-Based Midcourse system. An interceptor launched from Vandenberg Air Force Base, California intercepted a target launched from Ft. Greely, Alaska. While an intercept did occur, the countermeasures that were used (two balloons) failed to deploy. the decoys were reported by MDA to be “less sophisticated than the countermeasures flown in 2002,” so the interceptor would have been less challenged than with decoys in tests 6 years prior to FTG-5
2010 to Current Day	
31 January 2010	Intercept test (FTG-6) of a target missile. The target missile was launched from the US Army’s Reagan Test Site at Kwajalein Atoll in the Republic of the Marshall Islands. Approximately 6 minutes later, an interceptor was successfully launched from Vandenberg Air Force Base, California. Both the target missile and interceptor performed normally after launch. However, the Sea-Based X-band radar did not perform as expected and the interception failed
6 June 2010	In this flight test, a two-stage Ground-Based Interceptor (GBI) was launched from Vandenberg Air Force Base, California. After performing flyout maneuvers, the two-stage booster delivered an exoatmospheric kill vehicle to a designated point in space. After separating from the second-stage booster, the kill vehicle executed a variety of maneuvers to collect data to further prove the performance of the kill vehicle in space

(continued)

Table D.1 (continued)

15 December 2010	In this intercept test (FTG-6A), an intermediate-range ballistic missile target was launched from the Ronald Reagan Test Site on Kwajalein Atoll in the Republic of the Marshall Islands, and a long-range interceptor missile was launched from Vandenberg Air Force Base, California. The Sea Based X-Band radar (SBX) and all sensors performed as planned. The missile failed to intercept the target
September 2012	The National Academy of Science released a report entitled “Making Sense of Missile Defense,” which called the GMD system “deficient” with respect to all of the study’s fundamental principles for a cost-effective missile defense. It recommended a complete overhaul of the interceptors, sensors, and concept of operations
26 January 2013	Flight test (GM-CTV-01) of a three-stage Ground-Based Interceptor (GBI) launched from Vandenberg Air Force Base, California. The three-stage booster deployed the Exoatmospheric Kill Vehicle to a designated point in space. After separating from the booster, the EKV executed a variety of preplanned maneuvers to collect performance data in space. Engineering data from this test is being used to improve future intercept missions. This test is the critical first step in returning GMD to successful intercept testing
15 March 2013	Secretary of Defense Chuck Hagel directed the Missile Defense Agency, in response to advances in North Korea’s nuclear and missile programs, to field 14 more GBI by 2017, to bring the system to a full complement of 44 interceptors. He also canceled the fourth phase of the European Phased Adaptive Approach missile defense program, due to a lagging development timeline
5 July 2013	In this intercept test (FTG-7), a target missile was launched from the US Army’s Reagan Test Site on Kwajalein Atoll, Republic of the Marshall Islands, and a Ground-Based Interceptor missile from its silo at Vandenberg Air Force Base, California. The test required an exoatmospheric kill vehicle to separate from the GBI’s upper stage booster and maneuver to a collision course with the target. The kill vehicle failed to separate from the booster. Though the exact cause of the FTG-07 anomaly is not yet known, the EKV had failed to separate from the interceptor and booster on two previous occasions, first in July 2000 and again in December 2002
11 July 2014	The Pentagon changes its assessment of Iran’s ICBM prospects to “Iran has publicly stated it may launch a space launch vehicle by 2015 that could be capable of intercontinental ballistic missile ranges if configured as a ballistic missile”

(continued)

Table D.1 (continued)

8 September 2014	The Department of Defense's Inspector General released a report evaluating the quality control of the production of the GMD system's kill vehicles. It stated, "A combination of cost constraints and failure-driven program restructures has kept the program in a state of change. Schedule and cost priorities drove a culture of 'Use-As-Is' leaving the EKV as a manufacturing challenge. With more than 1800 unique parts, 10,000 pages of work instructions, and 130,000 process steps for the current configuration, EKV repairs and refurbishments are considered by the Program to be costly and problematic and make the EKV susceptible to quality assurance failures"
30 September 2014	The Ground-Based Midcourse System turned 10 years old. On September 30, 2004, the George W. Bush administration declared that the GMD system had achieved a limited deployment option (LDO) capability, meaning the system was now capable of being turned on and used if necessary. Only five interceptors were in place that day. The intercept test record was seven successful intercepts out of 16 attempts
5 November 2014	Admiral Greenert, Chief of Naval Operations, and General Odierno, US Army Chief of Staff, urged the Secretary of Defense to take a new look at the problem of defending against ballistic missiles. They stated that "the present acquisition-based strategy is unsustainable" and that the Pentagon must develop a "more sustainable and cost-effective," "long-term" approach to missile defenses
June 2015	A US Government Accountability Office report revealed two important problems with the GMD system. The Pentagon stated that it would delay "emplacing" the interceptors until a test had validated the fixes, but would not wait for a successful test before producing them. The reason: delaying the production and integration until a successful flight test was conducted "would unacceptably increase the risk to reaching the Secretary of Defense mandate to achieve 44 emplaced interceptors by the end of 2017"
14 July 2015	The negotiation of the Joint Comprehensive Plan of Action concluded. The agreement, reached by Iran and the P5+1 (China France, Germany, Russia, the United Kingdom, and the United States), substantially limited Iran's ability to develop nuclear weapons
October 2015	Congress directed the Missile Defense Agency to "commence the concept definition of a space-based ballistic missile intercept layer to the ballistic missile defense system that provides (1) a boost-phase layer for missile defense or (2) additional defensive options against direct ascent anti-satellite weapons, hypersonic glide vehicles, and maneuvering reentry vehicles"

(continued)

Table D.1 (continued)

January 2016	MDA performed a non-intercept test of the GMD system, meant to validate fixes and updates to the kill vehicle and to gather information about how well the system can discriminate target from decoys. While described by MDA as a success, later information came out that suggested that one of the motors on the kill vehicle did not restart after being shut down, and that the kill vehicle veered far off course from its nominal target
February 2016	North Korea successfully put its second satellite into orbit
December 2016	Congress scrapped the 1999 Missile Defense Act language and removed the modifier “limited” from the missile defense mandate, opening the door to building missile defenses intended to defend not only against the anticipated limited missile capabilities of North Korea and Iran, but also those of the peer and near-peer forces of Russia and China. Congress also called for the MDA to begin research and development, and to test and evaluate space-based missile defense programs
30 May 2017	Successful GMD test FTG-15 tested against what was described to be an ICBM-range target. It was a nearly head-on engagement of a test missile of around 5800 km. This brought the intercept test record to nine successful target destructions out of 18 attempts
June 2017	Russia publicly announced the launch of a satellite in June 2017, but insisted that its only function was to inspect the country’s own space-based systems for damage or other possible issues and potentially service and repair them Around this time, a high-ranking US diplomat alleged that the nation had deployed another smaller, more specialized satellite into orbit that had anti-satellite capabilities. This was at least the fourth such system launched by Russia since 2013. Along with the US’s own actions to increase its military capabilities, these developments demonstrated the ongoing weaknesses in the international framework surrounding hostile activities in space ^a
28 July 2017	North Korean missile test indicated that its ICBM appears to be able to reach major US cities
13 February 2018	Recent budget changes under the Trump administration have provided a major funding boost to US missile defense efforts over the course of this calendar year, allowing for the purchase of more GBI missiles atop the 44 already being used by the US ^b
17 August 2018	The US Congress tasks the Missile Defense Agency (MDA) with developing and demonstrating a boost-phase ICBM (and hypersonic weapon) intercept capability as soon as possible. One such concept is a space-based laser. Michael D. Griffin, the Undersecretary of Defense for Research and Engineering, expressed his belief that the US would achieve space defense through megawatt—class directed energy weapons in space within a decade ^c

(continued)

Table D.1 (continued)

18 August 2018	The US Air Force awarded Lockheed Martin Space Systems a \$2.9 billion contract to design and develop three Next Generation Overhead Persistent Infrared Geosynchronous Earth Orbit Space Vehicles. These are to replace the current Space-Based Infrared System. By 2023, they will host SBIRs ^d
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^aMissile Defense Advocacy Alliance. [Internet]. Russia has four potential “killer satellites” in orbit, at least that we know about. 17 Aug 2018. [cited 20 Aug 2018]. Available from: <http://missiledefenseadvocacy.org/threat-news/russia-has-four-potential-killer-satellites-in-orbit-at-least-that-we-know-about/>

^bWilliams, Ian. Missile Threat. [Internet]. How to keep US missile defense on the right track. 13 Feb 2018. [cited 20 Aug 2018]. Available from: <https://missilethreat.csis.org/keep-us-missile-defense-right-track/>

^cMissile Defense Advocacy Alliance. [Internet]. US targets a megawatt laser by 2023 and then deployment in drones and satellites for hypersonic and ICBM defense. 17 Aug 2018. [cited 20 Aug 2018]. Available from: <http://missiledefenseadvocacy.org/missile-defense-news/us-targets-a-megawatt-laser-by-2023-and-then-deployment-in-drones-and-satellites-for-hypersonic-and-icbm-defense/>

^dAmerican Machinist. [Internet]. Lockheed Draws \$2.9B USAF Contract for Missile Defense. 18 Aug 2018. [cited 20 Aug 2018]. Available from: <https://www.americanmachinist.com/news/lockheed-draws-29b-usaf-contract-missile-defense>

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