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Global Navigation Satellite Systems and Their Applications





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—Arthur C. Clarke (Wireless World, October 1945)

Before you become too entranced with gorgeous gadgets and mesmerizing video displays, let me remind you that information is not knowledge, knowledge is not wisdom, and wisdom is not foresight. Each grows out of the other, and we need them all.

—Arthur C. Clarke (Cited in: Joseph N. Pelton's *The Oracle of Colombo: How Arthur C. Clarke Revealed the Future*, (2015) Emerald Planet, Washington, D.C. Chapter 11)

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About the Author

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Chapter 1 Global Navigation Satellite Systems

Why Write a 'Short Book' on Global Navigation Satellite Systems?

Our modern world is interconnected with advanced technologies. All aspects of our lives are dependent on our ability to measure space and time every day. "Where are we and what time is it"? These two basic questions connect us to all aspects of our modern, technologically driven lives. Satellites, in this case, Global Navigation Satellite Systems (GNSS) also known as Positioning Navigation and Timing (PNT) satellites, have quickly become an integral part of our daily lives and are now an unseen but vital utility that is used throughout the world. A day without GNSS satellites would be a very bad day indeed. Most people in the world use GNSS systems every day, without even knowing it. Only when it disappeared would they understand just how much they depend on it for carrying out their daily activities.

What Is the Best Way to Grasp the Field of Global Navigation Satellite Systems?

The best way to grasp this field is to consider what would happen if our navigation and timing satellites were to suddenly be turned off. Although there would not be panic in the streets, the effects would be quick and the impact would be huge, and felt all over the world. Almost all aspects of our lives are driven by time, and GNSS satellites provide us with time to the accuracy of atomic clocks anywhere on the planet. Our Internet communications, the World Wide Web, banking and stock market transactions and power grids are all timed using GPS or other GNSS networks. A very large number of cars, ships and aircraft navigation systems rely on GPS, and even the International Space Station and other satellites high above our heads determine their positions using these satellites. These so-called GNSS or PNT satellites provide global and seamless timing and positioning in ways that are often hidden, but which are vital to the operation of our modern, technologically driven civilization. But that is not all.

There are currently over millions of jobs worldwide that depend on the GNSS technologies. Over 130,000 manufacturing jobs and over 3 million people are involved in some aspect of the downstream GNSS markets for their livelihoods. The commercial value of the direct and indirect markets are difficult to precisely define, but is in the range of US\$100 billion per year in the United States alone. Worldwide it exceeds \$175 billion. And this trend is accelerating, as more commercial applications of the new Chinese, Indian and European satellite PNT systems come online. The move from expensive, dedicated GPS receivers to smartphones with imbedded chips that provide PNT services at no additional cost has created a new and huge growth in new applications, such as Location Based Services (LBS).

Who Is Involved and What Are Their Various Perspectives?

The various national (and European Union) governments are the primary players in the development, launch and operation of these systems. There are (as yet) no private positioning systems. The U. S. government has pioneered the development and operation of the so-called Global Positioning System, or GPS, and this has been followed by Russia, China, India, Japan and (soon) the European Union. There are both upstream (providers of the enabling technologies) and downstream (markets that exploit the technologies) aspects to the GNSS markets. The upstream markets are dominated by large aerospace corporations that provide the ground segment (control systems) and space segments (satellites and launch vehicles), such as Raytheon, Honeywell, Northrop Grumman, Boeing, Lockheed-Martin, Thales, Astrium and NEC. In the downstream markets, key vendors are Garmin, Trimble, Leica, TOPCON, Tomtom, Magellan and Navteq. Google, Apple and Samsung are among the major users of GPS chips for the millions of smart phones that now have satellite navigation receivers. Millions, if not billions, of people around the planet have their lived affected by these systems every day.

The PNT industry is a high technology dual-use field. This means that this technology is used by national security and military systems for strategic defense purposes, but side-by-side, it is also used for civilian purposes—i.e., "dual use." Although the first systems designed by the United States and the former Soviet Union (now Russia) were for military purposes, the civilian market applications now include a much larger number of commercial vendors, products and uses. The low-price chipset manufacturers actually produce the largest numbers of units sold,

but these are a relatively small part of the overall commercial market. Major players include Texas Instruments, Qualcomm, Broadcomm, Infineon and ST Micro.

An unusual aspect of the GNSS market is that, other than the producers of ground equipment, launchers, and satellites, the entire market assumes that there will be free-of-charge signals provided by complex, billion-dollar government satellite systems. This is unique to the GNSS market, where all aspects of the commercial market receive the basic capability for free from government-designed and operated (and funded) systems. There is also a very wide range of PNT receivers, from GPS chipsets to inexpensive navigation receivers to car navigation systems and to very complex high-end scientific devices. These scientific receivers include centimetric surveying equipment (accurate to 1 cm), and dedicated ultra-exact timing devices. All of these rely on free government-provided signals.

Some Background and History

PNT services represent a relatively recent development in satellite applications, which has traditionally consisted of satellite telecommunications (by far the largest market) and space remote sensing. But since its development, there has been enormous growth in the use of global positioning and navigation systems such as the U. S. NAVSTAR Global Positioning System, or GPS. In fact, the commercial market for GPS now exceeds that of all space remote sensing. There are now several similar systems, so they are collectively referred to as precision Positioning, Navigation and Timing systems (PNT), or Global Navigation Satellite Systems (GNSS). These all share a common design and architecture, and use a constellation of complex satellites to provide very precise positioning, navigation and timing data globally, and they have tremendous application for a wide range of users around the globe.

The concept of satellite navigation is not really as new as many may believe. But first, let us consider what a satellite is. The term comes from the ancient Latin, *satellus*—a servant or slave of a powerful lord or master in ancient Rome, or an attendant. It was Galileo who first used the term in its astronomy context, to describe the moons of Jupiter he observed through his rudimentary telescope. Since the planets were named after the ancient Greek and Roman gods, he coined the term *satellites* (the plural of *satellus*) to describe the small bodies scurrying around the great planet, as servants bustle around their master. It is a fitting term, as artificial satellites, since the launch of Sputnik, have served us well. Satellites are orbiting servants of humanity, doing our bidding in communications, imaging, science and now, positioning, timing and navigation.

We have always used the stars and the Sun to navigate our way across the land and seas, but clouds were always a problem. The first proposed use of an 'artificial' navigation satellite appeared in a short story called "The Brick Moon" by Edward Everett Hale in 1869: ...he [Q] suggested the Brick Moon. The plan was this: If from the surface of the earth, by a gigantic peashooter, you could shoot a pea upward from Greenwich, aimed northward as well as upward; if you drove it so fast and far that when its power of ascent was exhausted, and it began to fall, it should clear the earth, and pass outside the North Pole; if you had given it sufficient power to get it half round the earth without touching, that pea would clear the earth forever..... If only we could see that pea as it revolved in that convenient orbit, then we could measure the longitude from that, as soon as we knew how high the orbit was, as well as if it were the ring of Saturn. But a pea is so small!" "Yes," said Q., "but we must make a large pea." Then we fell to work on plans for making the pea very large and very light.... It must stand fire well, very well. Iron will not answer. It must be brick; we must have a [hollow] Brick Moon." Edward Everett Hale, "The Brick Moon," Atlantic Monthly, Oct. Nov. Dec. 1869. (www.gutenberg.org/ebooks/1633)

The Brick Moon was to be 61 m in diameter (200 ft), and in a polar orbit 6,400 km (4,000 mi) high over the Greenwich Observatory in London, England, and be visible up to 6,400 km (4,000 mi) from its nadir. Mariners could determine their longitude (east-west) from this satellite in the same way that they use the North Star to find their latitude (north-south). Once the system was operational and proved beneficial, a second was to be launched over New Orleans in the United States, to cover the western Atlantic Ocean area. It was to be paid for by subscription, and by the maritime insurance companies such as Lloyds of London, in order to reduce navigational errors and ship losses at sea.

Arthur C. Clarke, the science fiction writer and space visionary who first proposed the use of the geostationary satellite orbit for satellite telecommunications, also proposed a satellite navigation system in his famous 1945 article that first described the use of telecommunications satellites. In this, he said: "...three satellites in the 24 h orbit could provide not only an interference and censorship-free global TV service for the same power as a single modern transmitter, but could also make possible a position-finding grid whereby anyone could locate himself by means of a couple of dials on an instrument the size of a watch." Arthur C. Clarke, *Wireless World*, October 1945.

He was right, and today we have both telecommunications satellites and positioning, navigation and timing systems that are an integrated part of our modern world. There were several early ground-based radio navigation systems, including LORAN and OMEGA, which paved the way for our current satellite systems. LORAN, from LOng RAnge Navigation, was a radio navigation system first developed in World War II by the United States. It used low frequency radio towers along the coastlines to broadcast radio signals and proved to be accurate for ships and aircraft from tens of kilometers to a few hundred meters, and was useful up to 2,400 km from the broadcast tower. The Coast Guard took over LORAN operation in 1958, and the system remained operational, with significant improvements, until the 1980s, when it was replaced by the newly developed GPS system.

The launch of Sputnik in 1957 by the Soviet Union was the first 'artificial' satellite, and it broadcast a beep that could be received around the world. Many people listened to the tone and were able to determine the orbital characteristics of the satellite by measuring the Doppler shift of the tone as it passed overhead.



Fig. 1.1 The transit 1-B satellite. (Image courtesy of NASA.)

Two American researchers at the Applied Physics Lab (APL), Johns Hopkins University in Maryland, William Guier and George Wiefenback, were able to mentally reverse this concept. They realized that if you had a satellite in a known orbit that was broadcasting a signal on a known frequency, then you could use the same Doppler analysis of that signal to determine your position on the ground. At the same time, another APL researcher, Frank McClure, was working with the U. S. Navy to develop a navigation system for the new Polaris nuclear ballistic submarine fleet, and he needed a reliable and robust ability for these submarines to quickly determine their position anywhere in the oceans, even after spending months under the sea. McClure proposed the concept developed by Guier and Wiefenbach to the Navy, and it was approved and developed as the TRANSIT satellite system. The first launch was in 1959 (only 2 years after Sputnik), and the system became operational in 1964. The system was only retired in December of 1996, with the completion of the more modern and more capable NAVSTAR GPS system (Fig. 1.1).

Transit used the Doppler shift of the broadcast signal from six satellites in offset polar orbits at an altitude of 1,000 km. The ship receiver had to lock onto the satellite signal for a period of 10–15 min in order to measure the frequency change, and the satellites were not in view continuously, so the system was only available at intermittent but regular intervals (Fig. 1.2).

What exactly is Doppler tracking? A position on the ground (or at sea) can be determined by tracking the Doppler effect on frequencies broadcast from a satellite. If the broadcast frequency is constant, the relative motion of the satellite towards or away from the receiver on the ground raises the frequency as the satellite comes towards you, and lowers the frequency as it moves away. If we know the precise orbit of the satellite and frequency of the signal that it broadcasts, then we can determine our position on the ground or at sea (Fig. 1.3).

The actual computation is:

$$\cos\left(A\right) = \left(\frac{\mathrm{fr} - \mathrm{fe}}{\mathrm{fe}}\right) \times \left(\frac{\mathrm{C}}{\mathrm{V}}\right)$$



Fig. 1.2 This shows a typical early transit receiving system onboard a navy ship. It was clearly not a portable system. (Image courtesy of the U. S. Navy.)



Fig. 1.3 Doppler shift positioning. (Figures courtesy of Argos.)

where:

```
C speed of light
V satellite speed relative to platform
fe transmit frequency (401.646–401.654 MHz for the Argos system)
fr receive frequency on the ground
```

You will see that this gives two positions where the cone intersects the surface of Earth. The correct one is determined by the previous location, or through repeat measurements on different passes. One limitation of the Doppler approach is that it will only derive your position on Earth's surface and cannot be used for aircraft in flight or in space.

The Soviet Union quickly developed a similar system, called Tsikada/Parus, that was based on the same Doppler approach. Tsikada (Russian for cicada, a chirping cricket) was the civilian system and Parus was the military one, but they shared a common design and satellite bus. A military constellation of six satellites became available in 1974, and a civil navigation program followed in 1978. The civil system was used by thousands of ships until recently, when it was superseded by the Glonass system.

The U. S. Navy Transit system worked well, and demonstrated that satellite navigation was possible and could be achieved in a practical manner. It was a huge leap forward, providing global and accurate navigation for the U.S. Navy anywhere on the surface of Earth. But it still had several major limitations for its intended use by U. S. submarines. You had to track the satellite for 10-15 min on the surface to measure the Doppler shift, leaving the submarine vulnerable and open to detection. There were only six satellites, so you had to wait until a satellite came into view, and so the system could not be used at all times. The position was only accurate to some 300 m, and it required a large amount of equipment in the ship (which got much smaller as the program went on). Nevertheless the Transit system equipment took up valuable space and power on a cramped submarine or ship. It also was not usable except on the surface of Earth, so there was not possible future use by aircraft or in space. Thus a decision was made to develop a second-generation system that used improved technologies to address these limitations. This was the origin of the now-commonly used NAVSTAR (Navigation Satellite Tracking and Ranging) Global Positioning System, or simply GPS.

There were several research programs that developed technologies that ultimately led to the GPS we use today. The U. S. Navy did research on a program called the Timation system. Researchers at the Naval Research Laboratory (NRL) developed a new concept in 1964 for satellite ranging, or measuring the range, or distance, to the satellites, rather than using the Doppler technique. The technique of satellite ranging provided not only better positional accuracy and precise time but could also be available on a continuous basis to an unlimited number of users. The first proof-of-concept Timation satellite was launched in 1967 into a polar orbit, and it proved the viability of the concept. The third Timation satellite, launched in 1974, was the first satellite ever launched into orbit with an atomic clock. This demonstrated the benefits of atomic clock-based satellite ranging.

At the same time, the U. S. Air Force was working on its own satellite navigation system, called Project 621B. This was also based on a satellite ranging concept, but one that would allow determination of altitude as well, which was, of course, vital for use in aircraft. Work on this program started in 1963, and the research led to many of the technologies that were incorporated into the GPS design. It relied on the use of satellite ranging and used a pseudo-random code that was broadcast by the satellite to a receiver on the ground. It provided altitude as well as positioning. All of this was clearly important for the Air Force. There was considerable rivalry and competition between the different military services at that time, but in 1973 the decision was made to combine aspects of both Timation and Project 621B into a single Defense Navigation Satellite System (DNSS) that would be used by all the U. S. military services. This system became the NAVSTAR Global Positioning System. The decision was made for the new system to be developed and operated by the U. S. Air Force, but that it would be suitable for Navy and Army use as well. It was originally intended to be a purely military system, with no civilian use allowed or, at best, that civilian use would be limited and of very poor precision, on the order of hundreds of meters. The new, integrated concept took the signal design of Project 621B, the orbits and orbital prediction techniques from Transit, and the atomic clocks from Timation and combined them into a single, operational design. Together these emerged as the GPS that we use today.

Chapter 2 Doppler Satellite Positioning, Telemetry and Data Systems

Before we consider the GPS system and its international equivalents, there are still two operational satellite systems that rely on the Doppler technique originally developed for Transit. These are the Argos environmental data system and the Cospas-Sarsat satellite search and rescue system. These systems, although not generally well known, provide excellent capabilities, and operate in a spirit of international cooperation and collaboration for the benefit of all humankind.

Argos Technology

The Argos positioning and data telemetry system is a satellite-based timing, positioning and data collection system that is dedicated to environmental research and uses. Unlike modern GNSS systems, it is a two-way telemetry system that is designed so that Argos terminals on the ground, in the air, or at sea can collect and store data and then broadcast the data up to a satellite, which passes it along to a ground station and then on to the end user. This is sometimes referred to as a 'store-dump' satellite data system. It can use both fixed and mobile platforms, and was first established in 1978 as a joint project between the United States and France. On the U.S. side was NASA and the National Oceanic and Atmospheric Administration (NOAA) and for France there was the French Space Agency (CNES). Argos was originally developed by the United States and France to use French hardware on existing U.S. NOAA polar-orbiting satellites. Although Argos operates with quite low data rates, it provides very cost-effective access to remote data collection devices around the world and is an important part of many global research programs. The system has been operated since 1986 under contract to CLS/Argos, based in Toulouse, France, with a U.S. subsidiary, CLS America, operating in Maryland. The European Meteorological Satellite Organization (EUMETSAT) has recently joined the partnership, as has the Indian Space



Fig. 2.1 The Argos data system, showing two wildlife systems transmitting data to a U. S. NOAA polar-orbiting satellite, where the data are sent to a ground station and on to the end user. (Image courtesy of Argos.)

Research Organization (ISRO). These new partners have expanded the capability of the overall system (Fig. 2.1).

The system includes the space segment (NOAA and now other polar satellites), the control segment (ground receiving stations and command and control centers), and the user segment (individual Argos devices). Argos devices are programmed to collect the data, store the data, and then transmit signals to the satellites at periodic intervals, set by the user.

There are many kinds of Argos transmitters available on the commercial market. The space segment now includes six polar-orbiting satellites flying in an 850 km altitude orbit (three NOAA polar orbiting satellites and three METOP European satellites operated by EUMETSAT). These make up the EUMETSAT/NOAA Initial Joint Polar System (IJPS). The satellites receive the data and store them onboard until they can download the data to a receiving station.

Argos has a total of over 40 automated ground receiving stations located around the world, with three main receiving stations that also collect all data on each pass, located at Fairbanks, Alaska; Wallops Island, Virginia; and Svalbard, Norway. The receiving stations automatically pass the data to the French and U. S. global processing centers, which then process the data from the various receiving stations and distribute the data on to the end users, often as an automated email message. Secure access is provided by the ArgosWeb website (http://www.Argos-system.org). This specially designed website can display data on world maps, or as tables and charts as defined by the user. Data can also be sent by the ArgosDirect automatic distribution system via email, ftp, or on CD-ROM. Data are archived for 12 months.

Users purchase Argos platforms, as the transmitters are called, both mobile or fixed, from one of several commercial vendors. These are fitted with various sensors to measure a wide variety of parameters, including sea surface temperature, salinity, wildlife parameters such as heartbeat, river or tide gage data, earthquakes and more. Each platform has a unique identifier and transmits the platform identification number and all collected data on 401.650 MHz. Each platform has a fixed repetition period, variable between 90 and 200 s, depending on the user requirements. Each platform transmission lasts less than 1 s, so the system can accommodate multiple platforms in the same area. The first generation of the system had platforms blindly transmitting the data using a transmission process akin to the so-called Aloha system. Users of this process simply hoped that the satellite would receive its signals, and if not it would do so on the next transmission. The new generation devices are smarter, as described below (Figs. 2.2 and 2.3).

The Argos systems fly as small 'parasite payloads' on the six NOAA Polar Orbiting Environmental Satellites (POES) and Eumetsat MetOp satellites. These satellites are in 100 min, near polar, Sun-synchronous orbits that are each offset from the other satellite orbits, so that they cover as much ground as possible in each day. Areas at the poles see the transmitter on each pass, acquiring 14 data takes per day, while areas at the equator get around 8–10 per day, day or night, rain or shine. Each orbit overlaps 25 % at the equator with the last pass, as shown in Fig. 2.4, as Earth rotates under the satellites in a polar orbit.

Each satellite covers an area 5,000 km across as it orbits Earth and can receive data from all Argos transmitters within this area. The satellite will be in view of a platform for approximately 10 min, but it only takes a second to transmit and receive the data.



Fig. 2.2 This shows the overall Argos system design. (Image courtesy of Argos.)



Fig. 2.3 The location of Argos ground receiving stations. Satellites receiving data while in view of a ground station can download the data in near real time. If over remote areas, the satellites store the data until in view of a ground station, rarely over 2 h. (Image courtesy of Argos.)



Fig. 2.4 Argos visibility area and orbit overlap. (Image courtesy Argos.)

The two processing centers offer redundant capabilities, with one near Washington, D. C., and one in Toulouse, France. These centers process and check the data, and then make it available to the end users, usually within minutes of receiving the data from the satellite. Transmissions within sight of one of forty ground receiving stations are downloaded in near real time, while remote ocean data, for example, have the data stored on the satellite until it is in view of a ground receiving station.

The data are processed using the Doppler shift technique described above, but modern platforms can also be fitted with GPS receivers, and the more precise GPS

Data - 54 kena 🔟 🖬								1 🖬 🖻	
	Platform ID No. 8	Platform type El	Obs. Date 1	Latitude E	Longitude El	Loc. date H	Level B	ATMPRES H	SEATEMP B
~	69005	DRIFTER	2008/07/27 03:40:00	10* 58' 45'N	65*52 29W	2006/07/27 01:25:42	0	1013.1	26.23
~	69005	DRIFTER	2008/07/27 04:40:00	10° 58' 45'N	65° 52 29'W	2008/07/27 01 25:42	0	1012.9	26.149
*	69005	DRIFTER	2008/07/27 05:40:00	11* 22* 13*N	65* 20' 19'W	2008/07/27 09:40:36	0	1012.5	25.989
~	69005	DRIFTER	2008/07/27 06:40:00	11° 22' 13'N	65° 20' 19'W	2905/07/27 09:40:36	0	1012.3	26,069
~	69005	DRIFTER	2008/07/27 07:40:00	11" 22" 13"N	65° 20' 19'W	2008/07/27 09:40:38	0	1012.3	26.23
~	69005	DRIFTER	2008/07/27 08:40:00	11* 22' 13'N	65° 20' 19'W	2008/07/27 09:40:38	0	1012.5	20.31
~	69005	DRIFTER	2008/07/27 09:40:00	11° 22' 13'N	65° 20' 19'W	2006/07/27 09:40:36	0	1013.0	26.39
~	69005	DRIFTER	2008/07/27 10:40:00	11" 22' 58'N	65° 17 59'W	2006/07/27 10:03:39	0	1013.2	26.39
~	69005	DRIFTER	2008/07/27 11:40:00	11° 22' 58'N	65" 17 59'W	2006/07/27 10:03:39	0	1013.7	26.47

Fig. 2.5 An Argos message. (Image courtesy of Argos.)

position and time can be automatically extracted from the data. All data are distributed in latitude/longitude using the WGS84 (World Geodetic System 1984) reference system. Estimated positioning error is processed for each reception. With GPS, the true position is within 20 m, and with the Doppler technique it can range from 1,500 to 250 m in accuracy, depending on several parameters. Due to technical issues, some passes cannot compute the Doppler position, and so may sometimes transmit the data parameters without coordinates. For terrestrial readings, a global digital elevation model (DEM) is automatically used in all ground mobile data to improve the precision of the location by including the altitude above sea level (Fig. 2.5).

Each platform has an ID, a type, the date, latitude and longitude coordinates, the precision level, and then the various data parameters. In the figure above, the platform was measuring seawater salinity and water temperature, each measured at 11 different sea depths. Argos readings are dedicated to studying and protecting our natural environment, and must be non-commercial in nature. New users simply fill out an online request, which is reviewed by the Argos Operations Committee. This committee consists of representatives from NASA, NOAA, Eumetsat, CNES, and ISRO. Once approved, the user fills out a Program Overview, describing their data parameters, ID numbers of transmitters, and other information. Before deployment the devices are tested under conditions similar to their anticipated in situ conditions, to ensure proper operations. Once deployed, the data are accessed via the ArgosWeb, ArgosServer, or ArgosDirect, ArgosShare, ArgosMonitor or WebServices methods as described in the Argos website (www. Argos-system.org).

Argos transmitters (originally called Platform Transmitter Terminals, or PTTs) can be purchased from several vendors, and the prices range between US\$2,500 and US\$4,500, depending on size, battery life, data storage, and other factors. Some are tiny, for attaching to small birds or other animals, while some are quite large and designed for use on permanent marine buoys or other fixed locations. Yet others are designed for deep-diving whales and can pop off and transmit their data after a fixed time (Fig. 2.6).

This example is a tiny 17 g (or just over a half ounce) solar powered system for bird tracking. It has been used to track gulls and kites, and has a 16-channel GPS, providing location accuracy of about 20 m, a solar panel for battery charging, and a three-year operating lifetime.



Fig. 2.6 A miniature 17 g Argos bird transmitter. (Image courtesy of Argos.)

Fees are based on PTT transmissions. The standard service costs US\$15 per day per PTT, with data only (no position) costing \$7.50 per day. To access via email, Internet, ftp or by fax, the cost is US\$0.12 per kilobyte. This is a very modest cost for such a valuable service.

Argos Applications

There are over 21,000 Argos transmitters in use today, and the system can accommodate many more (so think up a novel application!). The number of applications is very broad, including monitoring of marine, land, wildlife, hazardous materials tracking, ocean racing, and disaster applications. Self-contained Argos systems are used to transmit housekeeping data from remote dams, pipelines, power stations and other sites, many located in inaccessible regions that do not have permanent staff.

Over 6,000 drifting and moored ocean buoys transmit global ocean data on a continual basis via Argos. Information such as wind speed and direction, air pressure, air temperature, water temperature and salinity are collected throughout the world's oceans. These provide valuable 'ground truth' data to calibrate satellite data, and are important parts of the World Climate Research Program (WCRP). Over 70 % of all Argos data are voluntarily exchanged globally for use in ocean and weather prediction models (Fig. 2.7).

Here is a sample transmission:

Marine station WMO 12345 on 29 January 1993 at 06:00 UTC, Latitude = 21° 22 min. North, Longitude = 43° 52 min. West, Wind Direction = 70°, Wind Speed = 23 m/s, Air Temperature = 12.5 Celsius, Temperatures at selected depths: Surface: 12.4 C, 10 m: 8.2 C, 150 m: 2.2 C. Salinity at 10 m: 35 ppm."

A global marine drifter array operates around the world, with drogues set at different depths to map ocean currents and collect other data (Fig. 2.8).



Fig. 2.7 Argos marine buoy. The drogue can be set at different depths to track underwater ocean currents. (Images courtesy of NOAA.)



Fig. 2.8 Status of Global Drifter Array. Colors indicate different types of buoys. (Image Courtesy of NOAA.)



Fig. 2.9 NOAA fixed ocean buoy array locations and marine-anchored buoy. (Images courtesy of NOAA.)



Fig. 2.10 Argo float network showing drifting floats in the world's oceans. (Image courtesy of Argo and the Japanese Agency for Marine-Earth Science and Technology.)

Fixed marine buoy networks are also located around the world's coastlines, the arctic sea, and across the Pacific Ocean, providing vital wind and wave height data. These data are available in real time through the NOAA National Data Buoy Center's website (http://www.ndbc.noaa.gov) (Fig. 2.9).

Over 3,000 Argo program devices (different from Argos) that are called floats are in the world's oceans. These collect water temperature, salinity and current data for the upper 2,000 m of the world's oceans each day. They drift at 1,000 m depth for days, and then dive to 2,000 m every 10 days and rise to the surface, collecting water profile data. On their return to the surface, they broadcast the data collected using the Argos system, and then start the process again. These are operated by many nations around the world, and the data are all freely shared with the international scientific community (Fig. 2.10).



Fig. 2.11 Over 8,000 fishing vessels use the ArgoNet fleet tracking system. (Image courtesy of ArgoNet.)

One of the most interesting applications is the use of Argos transmitters on fishing vessels to monitor exclusive economic zone (EEZ) compliance. These vehicle monitoring systems (VMS) provide data that are admissible in court regarding illegal fishing operations and are used around the world to monitor fish catch data and EEZ fishing compliance in the United States and other countries. The ArgoNet system provides a turnkey package for monitoring fishing fleet operations. Over 8,000 fishing vessels around the world are equipped with these systems (www.argonet-vms.net), and several nations have successfully prosecuted illegal fishing operations within their EEZ limits.

Since 2005, the United Kingdom has required all fishing vessels over 15 m to have installed onboard a satellite tracking system, and using this system they have successfully prosecuted offenders. The use of ArgoNet data has been upheld by the British courts. Vessels can upload their position and catch information (by zone and species) automatically to the appropriate regulatory agency. The International Maritime Organization has mandated that all vessels over 500 gross tons must install an Argos-based Ship Security Alert System (SSAS) that allows crews to send a message in case of acts of piracy, and to allow fleet managers to track their vessels worldwide (Fig. 2.11).

Icebergs in the North Atlantic Ocean are routinely tracked using specially designed Argos buoys that are dropped from U. S. Coast Guard aircraft onto large icebergs. This is part of the International Ice Patrol program created after the sinking of the *Titanic*. The location of these dangerous icebergs can then be broadcast to ships at sea.



Fig. 2.12 Stork migration tracking using Argos. (Image courtesy of Argos.)

One of the most important uses of Argos is for wildlife tracking. Thousands of animals, ranging from migrating birds to deep-diving whales and land animals, are tracked across the globe using Argos devices. These have revolutionized our understanding of the migration patterns of many species of animals, feeding and breeding patterns, and more. Some of these miniaturized Argos transmitters can fit on the smallest birds and can track movements for over a year. Black storks (*Ciconia nigra*) travel some 4,000 km each year in an annual migration between Africa and northern Europe. Their migration patterns were tracked using tiny Argos receivers weighing only a few grams. One stork moved some 5,320 km from Prague to wintering grounds in central Africa, with daily migration distances between 150 and 350 km per day. One tracked bird flew some 476 km in a single day over the Sahara Desert (Fig. 2.12).

Marine species are also tracked, including deep-diving species of whales, sharks, marine turtles and more. Information on depth of dives, temperature, duration of dives and more can be automatically collected and received as email by the researchers. Land species such as artic caribou are routinely tracked on their annual migration routes.

Important public health applications include transmitting information about hospital and clinic admissions, food status, and even remote school attendance levels. Argos systems can provide vital early warning for human and environmental disasters in the most remote locations of the world by transmitting flood, earthquake and other data.

The Argos network has been in operation since 1978, about the same time that the GPS system was introduced, and Argos technology has changed significantly since then. The new Argos-3 next-generation system is now in the process of being implemented with the launch of Eumetsat's MetOp satellite. This new capability includes many improvements, including two-way communications (down to the Argos device, now called Platform Messaging Transceivers, or PMTs). The updated system has greater data volume transmitted, more efficient data collection and battery savings, and remote control and re-programming of the PMT while in operation. The original system allowed for data ranging from 32 to 256 bits, which is now increased to 4,608 bits per satellite pass, nearly 20 times the previous limit. Although the original system had transmitters constantly broadcasting, waiting for a satellite to come overhead, the new design allows receivers to know when satellites



Fig. 2.13 Argos data transmission per pass. (Image courtesy of Argos.)

will be overhead and to only broadcast in these windows, and then the satellite can broadcast down to the PMT that it has successfully received a transmission of data so that it can stop broadcasting, thus saving battery life and extending PMT lifetime. System users can also now send short messages to their transmitters, to alter the transmission schedule, change data collection parameters, or re-program their platforms. The new system is fully compatible with the existing Argos 1 and 2 systems, but significantly increase the utility and efficiency of the overall system (Fig. 2.13).

Cospas-Sarsat

The second Doppler-based satellite system still in use is the Cospas-Sarsat Satellite search and rescue system (http://www.cospas-sarsat.int). This is another excellent example of Cold-War era cooperation in space applications. The system is designed to take the search out of search and rescue operations, and was originally a collaborative project of the United States, Canada, France and the USSR. It was founded in 1979, and there are now 43 other nations and entities who are involved in this vital service. These include the four original parties to the Cospas-Sarsat agreement, 26 ground segment providers, 11 user states, and 2 participating international organizations. Cospas is short for *Cosmitscheskaja Sistema Poiska Awarinitsch Sudow* (Russian for "space system for search of vessels in distress") and Sarsat is short for "search and rescue satellite-aided tracking." (Figs. 2.14 and 2.15).

Studies show that aircraft accident survivors have a greater than 50 % survival rate if they are rescued within 8 h, but this drops to less than 10 % after 2 days. Search and rescue is very costly and dangerous and is often conducted in bad weather and inaccessible terrain. Satellites offer an excellent way to improve this



Fig. 2.14 The Cospas-Sarsat mission patch. (Image courtesy of Cospas-Sarsat.)



Fig. 2.15 A map showing the current Cospas-Sarsat participating nations. (Image courtesy of Cospas-Sarsat.)

process. The Cospas-Sarsat system originated after the October 16, 1972, air crash in Alaska that killed two members of the U. S. Congress, House Majority Leader Hale Boggs and Alaska Congressman Nick Begich. A massive search program was initiated, with thousands of soldiers, aircraft and even military reconnaissance satellites used in the search, but no trace of them or their aircraft was ever found. The U. S. Congress requested that NASA investigate the use of satellites for search and rescue, and eventually mandated all U. S. commercial aircraft to use distress beacons.

The Cospas-Sarsat system is very similar in design to the Argos system, which was developed around the same time. Both were designed as small parasite payloads to be mounted on NOAA polar-orbiting environmental satellites. The Cospas-Sarsat program added similar payloads onto two Russian satellites for additional coverage (Fig. 2.16).



Fig. 2.16 The Cospas-Sarsat system. A signal is sent to a satellite from a crashed plane or sinking ship, and the signal is forwarded to an automated ground station, and from there to a mission control center and rescue coordination center. (Image courtesy of Cospas-Sarsat.)

The space segment originally consisted of satellite payloads on two U. S. NOAA and two Russian Nadejda polar-orbiting environmental satellites that received the distress signal on 243 MHz (military) and 121.5 MHz (civilian) from a distress beacon. The satellite then passed the message along to one of several automated ground receiving stations (local user terminals) around the world on 1,433.3 MHz. The message was then transmitted to the appropriate national search and rescue coordination center, which managed the search and rescue operation. Search aircraft could then home in on the distress beacon broadcast. The current constellation includes five LEO (3 NOAA and 2 EUMETSAT) satellites in Sunsynchronous orbits at 850 km altitude and an orbital period of 100 min and several GEO satellites as well. The original 243 MHz (military) and 121.5 MHz (civilian) frequencies were updated to a single, dedicated 406 MHz frequency in 2009. The LEO satellites can receive alerts in a 6,000 km wide area, and the satellites are in view for approximately 15 min from the ground on each pass. Any point on Earth will be within view of one of the satellites within a maximum of 2 h (Fig. 2.17).



Fig. 2.17 The global network of Cospas-Sarsat ground stations and their coverage. Areas in *white* can receive alert messages immediately, while areas in *blue* have messages stored on the satellite until they come into range of a ground station. (Image courtesy of Cospas-Sarsat.)

The ground segment consists of a network of automated local user terminals (LUTs) around the world, some of which work with the LEO satellites (LEOLUTs) and some with the new geostationary satellites discussed below (GEOLUTs). These take the message from the satellite and pass it along to the appropriate national mission control centers (MCCs) for action and to direct the search effort. There are currently 31 mission control centers around the world, 58 LEO automated ground stations and 22 GEO automated ground stations, and a total of 6 LEO and 9 GEO satellites provided by the United States (GOES), Russia (Electro-L and Louch), Eumetsat (MSG) and India (INSAT).

The user segment consists of low cost distress beacons for aviation, marine and, recently, individual use. There are over 1.2 million distress beacons in use worldwide. EPIRBs (emergency position indicating radio beacons) are marine systems and are widely used on commercial and pleasure vessels. They can be triggered manually or be automatically activated when exposed to water, and can automatically detach, activate and float if a vessel sinks. The message can be pre-programmed with the name and owner of the vessel, number of people on board, cargo, etc. Specialized ship security alert devices (SSAS) are used to report incidents of marine piracy (Fig. 2.18).

Aviation ELTs (emergency locator transmitters) are used in all commercial and most private aircraft, can be manually activated, and are automatically triggered if a sufficient G-force is applied in a crash. These originally broadcast on the international aviation distress frequency of 121.5 MHz, in addition to 406 MHz, but the 121.5 frequency was phased out in 2009. Recently, personal locator beacons (PLBs) have been offered to backpackers and others, originally in a pilot project in Alaska. This brings satellite search and rescue to individuals, such as campers and explorers. One of the many mysteries with regard to the missing Malaysian

The following is an example of a 406 MHz maritime beacon message:



Fig. 2.18 An example of a Cospas-Sarsat marine EPIRB message. (Image provided by the author.)



Fig. 2.19 Cospas-Sarsat marine, aviation, personal and safety-at-sea beacons. (Image courtesy of Cospas-Sarsat.)

airline (Flight 370 of March 8, 2014) is why the emergency locator transmitters did not go off and alert the SARSAT global search team as to the exact crash location (Fig. 2.19).

The first satellite launch was in 1982, and the system was operational in 1984 using two U. S. NOAA polar- orbiting satellites and two Soviet Nadejda satellites. Using Doppler techniques, it provided approximately 1 km positioning, which was judged to be sufficient for global search and rescue use. Worldwide, over 35,000 people have been rescued around the world in over 9,000 individual searches over the lifetime of the program (Figs. 2.20, 2.21 and 2.22).

Many current generation systems also include GPS receivers, thus significantly improving the location provided from 1 km to less than 20 m. Recently, the system



Fig. 2.20 Cospas-Sarsat rescues in 2011, where some 2,313 people were saved in 644 individual operations. (Image courtesy of Cospas-Sarsat.)



Fig. 2.21 This shows the number and type of Cospas-Sarsat operations from 1994 to 2012

Fig. 2.22 The type of SAR event for 2012. (Image courtesy of Cospas-Sarsat.)





Fig. 2.23 This shows the overlapping GEOSAR coverage provided by U. S., Indian and EUMETSAT geostationary satellites. (Image courtesy of Cospas-Sarsat.)



Fig. 2.24 The MEOSAR and GEOSAR Cospas-Sarsat architecture. (Image courtesy of Cospas-Sarsat.)
has been expanded to include receivers in geostationary orbit, as it was determined that existing distress beacon messages could be received at that distance. If the beacon is equipped with a GPS, the GEOSAR constellation provides near-instant alerts, using the U. S. GOES, Indian INSAT and EUMETSAT MSG satellites. Because the GEO satellites are not moving relative to the ground, they cannot use Doppler tracking and only work with GPS-equipped beacons (Fig. 2.23).

The next generation of capability will be provided by the addition of a MEOSAR system, with Cospas-Sarsat receivers to be included on all next-generation U. S. GPS 3, Russian GLONASS, and ESA Galileo satellites. The U. S. component is called DASS, the distress alerting satellite system, designed by NASA (Fig. 2.24).

These three constellations will be fully compatible and interoperable, and will provide GPS accuracy using GPS-enhanced beacons, but will also provide improved location data for traditional Doppler-only systems. These three overlapping systems, LEOSAR, MEOSAR and GEOSAR, are complimentary, and each provides enhanced capabilities. For example, the LEOSAR satellites provide superior detection near the poles, where GEOSAR signals are weak.

Argos and Cospas-Sarsat are excellent examples of the powerful benefits of space technology for practical applications, and are excellent examples of international cooperation in space for the benefit of humankind.

Although Doppler-based systems, all dating back to the 1970's, have excellent capability, there are also significant limitations to the Doppler approach. Receivers need to maintain a track on a satellite for several minutes, and the coverage is not global. Doppler also does not allow for elevation differences; thus, it is not useful for aviation or space consumers. These limitations led to the development of the next generation of space positioning systems, the U. S. NAVSTAR global positioning system, or GPS.

Chapter 3 Precision and Navigational PNT Systems

The NAVSTAR GPS System

The U. S. NAVSTAR GPS system was the first and is still by far the most commonly used advanced satellite navigation system. It is made up of three segments: the space segment (a constellation of satellites in orbit), the control segment (ground stations and control centers that operate and oversee the system), and the user segment (your smart phone or hand-held GPS receiver). A brief timeline of the GPS systems shows that development began in 1973 (to replace TRANSIT), with the first satellite launch in 1978 and full, global operational capability achieved in 1993. This global capability continues today and is assured, free of cost to all users, into the future.

The intention of the NAVSTAR design was to provide a major improvement over the TRANSIT system in all areas, by designing a global system that would put all of the expensive and large equipment either in the space or control segments. This would leave to the global-using community an unlimited number of passive, small and portable receivers that could be used 24/7, anywhere on Earth, in the air, and up to low-Earth orbit, and in all weather conditions. (The accuracy in low Earth orbit, however, is not as great as it is on Earth's surface.)

The system was initially designed to be a strictly military capability with a very degraded civilian component, but this all changed in 1983, when President Ronald Reagan, in response to the Soviet shooting down of Korean Airlines Flight 007 on September 1, 1983, ordered free civilian access to what had originally been designed as a strictly military capability. In 1996 U. S. policy established joint civil and military management of the system, and in 1997 the U. S. Congress passed a law requiring that the civilian GPS signal shall be provided without cost or user fees. President Bill Clinton turned off selective availability (SA), which significantly degraded the civilian system in 2000, and in 2007 it was announced that SA capability would no longer be built into the next generation of GPS III



Fig. 3.1 The three segments of GPS—the ground segment, user segment and control segments. (Image courtesy of the U. S. GPS office.)



satellites. A major upgrade of both the satellites and ground infrastructure was started in 2003, which significantly improved the operation, precision and management of the overall system.

There are three segments that make up the GPS (and all other PNT systems): the space segment, the control segment and the user segment (Fig. 3.1).

The GPS space segment consists of a minimum of 24 satellites in six equally spaced orbital planes inclined 55° to the equator, at an altitude of 19,300 km (12,000 mi), so that each satellite orbits Earth two times per day. We refer to this as the GPS "birdcage" (Fig. 3.2).

There are a total of four to six satellites in each plane, so that a minimum of four satellites will be in view anywhere on Earth. (Normally there are far more, but it takes four for the system to compute your position, as described below.) This minimum number of satellites in view is basic to how the system works. The constellation requires a minimum of 24 satellites for global coverage, but often has up to 32. Many of these are visible, and the satellites are constantly rising and setting above you wherever you are, in an ever-changing pattern and geometry. Software in your receiver chooses the best four satellites to use. The spot where the various spheres intersect, created by the transmission distances from the satellites to the ground, represents where you are at any particular moment. If only three satellites are visible, software embedded in the GPS receiver can indicate which of two possible positions is where you are located. This is because the point ruled out would be far off the surface of the planet or underground (Figs. 3.3 and 3.4).

Satellites are launched one at a time from Cape Canaveral, Florida, on either Atlas or Delta rockets. The contractors that build the satellites are chosen by competitive bids and are built in batches, reducing cost. They have been constructed by both Boeing and Lockheed-Martin. The system is managed for the U. S. government by the U. S. Air Force and has been operational since 1978, with global coverage since 1994.

The satellites are in very high orbits for several reasons, including a larger viewing area on the ground (we need four in view to compute our position), more precise orbits (due to the distance from Earth), and survivability from attack (as it



Fig. 3.3 A Boeing Block IIF next-generation GPS satellite under construction and in orbit. (Image courtesy of the Boeing Company.)



Fig. 3.4 An exploded diagram showing the internal components of a Lockheed Martin Block IIR satellite. (Image courtesy of Lockheed Martin.)



Fig. 3.5 The GPS orbit, also showing the geostationary arc of communications satellites and low-earth orbit satellites close to the planet. (Image courtesy of NASA.)

was designed as a military system). These are all important factors in terms of how the system operates and for providing the required level of precision. Each satellite also contains a sensitive nuclear burst detector (NUDET) system, so the constellation also provides instantaneous reporting of any nuclear detonation on the Earth, at sea, or in the atmosphere (Fig. 3.5).

Control Segment

The GPS control segment includes the master control station at Schriever Air Force Base in Colorado Springs, Colorado, and an alternate control station at Vandenberg Air Force Base in California. In addition, there are 12 command and control sites that are used to communicate with the satellites, and 16 monitoring stations located around the world that also collect satellite data. This gives the USAF 2nd Space Operations Squadron, which runs the system for the U. S. government, daily operational control over the space segment. The automated monitoring stations track the satellites as they pass overhead and relay the data back to the master control station.

There are four control stations, located in Kwajalein Atoll, Ascension Island, Diego Garcia Island, and Cape Canaveral, Florida, that are used to communicate with the satellites. These stations are used to update atomic clock synchronization, provide navigation updates, and feed other data to them. These four sites are located in highly secure facilities, and are equally spaced around the world in reasonably close proximity to the equator (Fig. 3.6).

The user segment is your smart phone or dedicated GPS receiver. There is a wide range of dedicated GPS receivers available. These range from smart phones and inexpensive hand-held units to dedicated car navigation systems with moving map



Fig. 3.6 The GPS control segment. (Image courtesy gps.gov http://www.gps.gov/systems/gps/ control/)



Fig. 3.7 Common hand-held and auto GPS receivers. (Image from Wikimedia Commons http://en.wikipedia.org/wiki/File:GPS_Receivers_2007.jpg.)



Fig. 3.8 The AN/PSN-8 military GPS receiver, the first design. (Image courtesy of the U. S. Army.)

displays. At the higher end are aviation and marine systems that are linked to inertial navigation systems and ultra-precise surveying systems with sub-cm accuracy that cost tens of thousands of dollars. The design of the system allows for an inexpensive and small receiver to provide reasonably precise information to users around the world because all of the expensive and complex parts (such as the incredibly exact cesium atomic clocks) are in either the space or control segments (Fig. 3.7).

The original GPS receiver was the AN/PSN-8 military system. It was a one-channel receiver that weighed 8 kg (17 lbs.). Some 1,400 were manufactured between 1988 and 1993 for a cost of US\$45,000 each. The original requirement was a total





of 700 for all of the U. S. Army. Compare this initial requirement with the fact that over 720,000 commercial GPS units were sold in 2012 alone and probably a much higher number in 2013 and 2014. The continuing high demand for GPS receivers demonstrates the tremendous commercial utility of GPS beyond its original military roots in this era of "dual use" military and civilian applications (Fig. 3.8).

The current U. S. military hand-held GPS receiver is the AN/PSN-13 Defense Advanced GPS Receiver, called the DAGGER. This is a dual frequency military receiver that can automatically decode the military encrypted P-code GPS signal that is not available to civilians. It also has anti-jamming and anti-spoofing features. Over 125,000 of these have been ordered for the U. S. military and allies, a purchase worth over US\$300 million. These contain sensitive military encryption components, and it is illegal for civilians to purchase or be in possession of one of these military-grade receivers. There are also multiple military aviation, marine and space systems (Fig. 3.9).

GPS can also be very useful for civilian field data collection. The IkeGPS, as an example, is an innovative, integrated GPS field data collection system available commercially. It consists of a single, hand-held and ruggedized device with a sub-meter GPS receiver, 5 megapixel digital camera, digital compass, laser range finder, and mobile computer. This system can be used for very rapid and accurate data collection and disaster damage assessment in the field. The laser range finder allows the user to remotely collect position data of features that cannot be safely accessed, up to 1,000 m away. (http://www.Ikegps.com) (Fig. 3.10).

As we now have multiple GNSS constellations deployed by several different countries, many manufacturers are developing multi-constellation receivers that operate in the frequencies used by these other satellite networks. Trimble, a major



Fig. 3.10 IkeGPS hand-held, integrated data collection system. (Image courtesy Ikegps. www.ikegps.com.)

manufacturer of GNSS receivers, in 2014 announced a new model, the BD-930, which has a triple-frequency GPS/Glonass/Beidou/Galileo receiver with a built-in UHF module to allow high-speed data transfer. This will provide centimetric realtime kinematic positioning, and was available in the market as of July 2014. Millions of the latest model smart phones from Samsung, iPhone, Blackberry, Asus, Nokia, Motorola, Alcatel and ten other brands have a dual GPS and Glonass receivers.

How GPS Works

The GPS system is actually a very precise timing system, and each satellite has several atomic clocks and constantly broadcasts several coded messages on different frequencies that are received by your GPS unit. GPS is all about time.

Atomic clocks are the most precise means of measuring time yet devised. A cesium atomic clock, as used in GPS satellites, operates by exposing cesium atoms to microwave energy until they vibrate, and then measuring the frequency of these vibrations as a measurement of time. Modern cesium clocks measure this vibration to an extraordinary standard, to 2 or 3 parts in 10^{14} . Another way to consider this is an accuracy of 2 ns per day, or two billionths of a second. The second itself was defined by the cesium atomic clock method in 1967, and it was in 1971 that International Atomic Time, or TAI (the French version) was defined. This is the basis of Coordinated Universal Time, or UTC, which is the basis for all terrestrial time today.

In order to maintain the most accurate time possible, TAI is actually an average of over 200 atomic clocks in multiple facilities around the globe, because gravity affects this measurement. Also, because of the relativity of time with regard to velocity that Einstein discovered, the most precise receivers make an adjustment with regard to the fact that time on a speeding satellite is a tiny bit slower that on Earth. General Relativity predicts that a clock in a strong gravity field (Earth) will operate at a slower rate, while Special Relativity predicts that clocks that move fast, like on a satellite, will be slightly slower. The fascinating fact is that these two effects nearly cancel each other out at sea level. The actual numbers are that a GPS clock away from Earth's gravitation will be about 45,900 ns faster per day, and it will be slower by about 7,200 ns/day. The atomic clocks on the satellites are pre-set on the ground to compensate for these differences, and actually run slightly off on the ground but are accurate once in orbit, thus confirming Einstein's theories of General Relativity and Special Relativity.

The actual measurement of time and its terrestrial and astronomical applications is thus very complex, but this should allow a basic understanding of how GPS time is computed.

The GPS civilian, or Coarse Acquisition (C/A code) and military code (Precision or P code) work in related but slightly different ways that are referred to as codebased GPS. The way the civilian system works is as follows. The C/A code broadcasts a repeating stream of microwave signals consisting of 1,023 bits, called the pseudorandom binary code. This is transmitted at 1.023 Mb/s and repeated every millisecond. Each satellite broadcasts a unique code, and the receiver uses code division multiple access (CDMA) telecommunications processing to recognize multiple satellites on the same frequency. Each satellite also broadcasts a navigation message that contains the satellite's ephemeris data, which allows the receiver to calculate the precise position of the satellites in orbit, as well as data about the health and status of each satellite, which is referred to as the almanac. These navigation messages are modulated on top of the C/A and P(Y) codes at 50 bits/s. The data stream is broadcast at very low power, barely above the random background noise level. This is referred to as the pseudorandom code that is received by your GPS device. Civilian GPS receivers have limitations set for speed and altitude, to prevent their use for military purposes. Any civilian GPS traveling over 1,000 knots (1,852 km/h) or over 65,000 feet altitude (19,812 m) will cease operating.

The military P-code is also a pseudorandom code, but it is much longer, on the order of 720 Gb, and only repeats each week. It is transmitted at a higher rate of 10.23 Mb/s. The P-code is actually a short segment of a master code, of some 26.7 Tb length, so each satellite repeatedly broadcasts its segment of this longer master code. In order to prevent unauthorized use or interference with the P-code it is encrypted, and it is modulated with a W-code to generate a classified Y-code, which is what is actually transmitted. This is referred to as the P(Y) code, which can be processed only by military GPS receivers. It provides higher precision positioning than the civilian code and works at higher velocities and altitudes.

The navigation message has three individual parts: the GPS date and time and satellite status is the first, the second part is the ephemeris data, and the third is the almanac, with information on the health of each satellite. The ephemeris data are updated and valid for only 4 h, while the almanac data are good for up to 180 days but are updated daily. The almanac data helps the receiver to decide which satellite to search for and use. Once a satellite signal is received, then it downloads the ephemeris data for that individual satellite. The ephemeris data is required before the receiver can use that satellite for navigation.

The almanac data includes status and orbit data for that satellite, ionospheric information (a major source of GPS error) and information about GPS time. The almanac is useful when you power on your receiver, so that you can know which satellites are visible. With older, single-channel receivers, the almanac data also allowed for some correction of ionospheric delay.

Satellites update their ephemeris every 2 h through the control segment, and the ephemeris is valid for up to 4 h at a time. Inexpensive GPS receivers can take up to 36 s to download these housekeeping data, due to the very low data rate. When you turn your GPS on after moving a long distance, it will take some time for the system to 'reinitialize' using this procedure before it can begin working. These data are then modulated onto the GPS carrier frequency for broadcast down to Earth. Two original frequencies, 1575.42 MHz (the L1 frequency) and 1227.60 MHz (L2), are used. The C/A code is transmitted on the L1 frequency, while the P(Y) code is broadcast on both L1 and L2.

Your civilian GPS receiver also has a copy of the same 1,023 bit PRN code, and software in your GPS receiver slides its copy of the signal sequence to match the signal received from a GPS satellite, as each satellite signal is received. It processes



Fig. 3.11 Matching the time difference in the GPS code. (Image courtesy of the USAF.)

the difference in the timing of the signals to determine your local position and time by comparing the signal being broadcast by each satellite and the same code on the receiver. To do this we need to know when the signal left the satellite and precisely what time it is at your receiver with a very high precision. This technique is referred to as satellite ranging, or determining your distance from a satellite, by measuring the time lag between when the code left the satellite and arrived at your receiver (Fig. 3.11).

To do this calculation using atomic clocks in both our satellites and our receiver would be simple, but the cost of atomic clocks precludes their use in our inexpensive receivers (US\$50,000 to \$100,000 per clock), so the GPS system uses a very clever trick to 'set' our inexpensive quartz clock in our receiver to the correct atomic time. The receiver listens to the signal from four or more satellites, and it can, using software, measure its own clock error by shifting through the codes. There is only one correct clock time that will cause the satellites to align correctly, and the receiver resets its clock to that time, getting an accurate 'atomic time' without the need of the expensive atomic clock. This is done on a continuous basis. Once this is done, it has a good approximation of GPS time, and then can compute your correct position.

The system works with a technique called satellite ranging, or measuring our distance from each GPS satellite. If we turn on our GPS receiver and get a signal from one satellite, we can slide through the code and determine the lag between when a signal left the satellite and when it arrived at our receiver. This allows it to compute that you are somewhere on a sphere that is a given distance from that satellite, all by measuring the time delay from when the PRN signal left the satellite and when it arrives at your receiver. The delay between when a signal left the satellite and when it arrives at your receiver is something between 65 and 85 ms, thus the need for extremely accurate atomic clocks to make the system work (Fig. 3.12).

So with one measurement from a satellite, we know that we are somewhere on a sphere that is the given time delay distance from that satellite. With two satellite signals, we know we are somewhere on two spheres, and the intersection of these two spheres is somewhere on the surface of an ellipse, as indicated in the Fig. 3.13.

A third signal reduces our position to one of two points, which is the intersection of the three spheres. Often, one of these two points can be eliminated using software because it is deep under the ocean or up in space, and our position can often be determined with only three satellites using software in our receiver. This was often used in the early stages of GPS, when there was not a complete satellite constellation (Fig. 3.14).



One measurement narrows down our position to the surface of the sphere

Fig. 3.12 Satellite range (distance) of one satellite. (Image courtesy of http://www.Trimble.com.)



Fig. 3.13 Satellite range (distance) from two satellites. (Image courtesy of http://www.Trimble.com.)

However, the system is designed and populated by enough satellites to always have a minimum of four satellites in view, and this provides us with our final position solution. As noted earlier there is only one unique place in the universe that is represented by the intersection of these four spheres, and that is your position. And you also have your precise time information as well. This allows us to use GPS to navigate anywhere on Earth, in the air, and up into low-Earth orbit (LEO), and to know the precise time as well (Fig. 3.15).

If we know the distance between the satellites and the receiver, and we know the speed of light in a vacuum, we can determine our location. The speed of light through a vacuum is about 300,000 km/s (actually 299,792,458 m/s or 186,282 mi/s). This means that light moves some 30 cm in one single nanosecond. Of course, we know the speed of light in a vacuum, but the signal has to propagate through Earth's



Fig. 3.14 Satellite range (distance) from three satellites. (Image courtesy of http://www.Trimble.com.)



Fig. 3.15 Satellite range (distance) from four satellites gives us our position. (Image courtesy of http://www.Trimble.com.)

atmosphere and ionosphere, and these bend and slow the signal, and thus cause positioning errors on the ground, because we think the satellites are farther away than they really are. So these are not perfect, intersecting spheres, in reality, and there are several sources of error mentioned in detail below, that cause uncertainty and lack of precision in determining our true location. One hundredth of a second error would give us a 3,000 km error on the ground, and even just an error of 1 ns gives us a 30 cm positioning error, thus the requirement for multiple, very precise atomic clocks in the system.

The United States has spent over US\$22 billion on the GPS system since 1973, including the construction and launch of over 120 satellites, 162,000 GPS receivers for U. S. military and other government and authorized users, and ground systems

costs. This does not include the cost of operation of the system, including staffing and payroll by the U. S. Air Force, which is accounted for separately, or the recent major upgrade of the system. This averages out to ~US\$750 million per year (data from Dec. '94 *Selected Acquisition Report*—GPS JPO) each year to manage and operate the GPS system. This is a tremendous amount of cost for a public benefit that is provided freely without cost to the world. This free access, and the power of knowing where we are and what time it is, is what has powered the enormous growth in the use of GPS technology. Yet it is also clear that it is the military applications for targeting of weapons systems that allowed these enormous investments in the GPS network to be made.

GPS Accuracy

The GPS Standard Positioning System (SPS) is the civilian C/A signal, and the accuracy of the system is determined by several factors. We refer to this as the GPS error budget. This consists of several variables, including the accuracy of the atomic clocks, ephemeris error (how certain we are of the exact position of the satellites), atmospheric errors, relativistic timing adjustments and also receiver error (how the receiver software computes the location). The atmosphere, both the ionosphere and troposphere, can bend GPS signals, making the satellites appear farther away than they are, thus causing error. This is the largest source of error. The precise location of the satellites is important, and the broadcast ephemeris data may not always accurately reflect their true position at a given time. Multipath interference is caused in urban areas, where the GPS signals can be reflected or bounce off of large buildings, again creating errors in the computed position. Selective availability (SA) was the intentional entering of both time and ephemeris data errors, in order to reduce the precision of the civilian GPS signals. This was the largest source of error, but has now been discontinued. If we add all of these up, we can see the total GPS civilian code error budget in Fig. 3.16.

It should be noted that nearly all of these sources of error can be removed using differential GPS (DGPS) and other techniques, which are discussed below. The geometry of the satellites used in computing our position is also very important. The effect of the geometry of satellites is referred to as the Dilution of Precision, or DOP, which originated with the LORAN system. Your receiver constantly computes the DOP, which is composed of several components, including the horizontal (HDOP), vertical (VDOP), position (PDOP), time (TDOP) and geometric (GDOP) components. In short, you want your satellites to be evenly spaced across the sky for the best DOP, and if you are in a canyon, for example, and your four satellites are all bunched together in the same area of the sky, you will have a poor DOP, and this reduces the precision of your computed location. Your DOP is a total measure, and ranges from a DOP of 1 up. Generally a DOP of 1–2 is excellent, 3–4 is good, 5–7 is fair and above 8 is considered to be poor. A DOP of greater than 20 can mean a position error of over 300 m. But it depends on your



Fig. 3.16 GPS error budget. (Image provided by the author.)



Fig. 3.17 This shows the standard GPS 15 m precision, WAAS enabled 3 m precision, and < 1 m DGPS overlaid on a map. (Image courtesy of the U. S. GPS office.)

application, and many users disregard the DOP entirely, while surveyors and geodesists pay very close attention. The computed error budget must be multiplied by your DOP to determine the actual precision of your position at a given time and place (Fig. 3.17).

Today, we can routinely get 15 m precision using the standard civilian capability alone. What this means is that 95 % of the time, our true position lies within a sphere that is 15 m across. This is sufficient for many uses, but with additional systems, such as wide area augmentation systems (WAAS), to be discussed later, we routinely get between 2 and 5 m precision. Using other techniques, we can have sub-cm precision, as will also be discussed later.

Figure 3.18 below shows 24 h of constant GPS positions using autonomous GPS, and how improved our precision is with WAAS, providing us with 1–2 m accuracy.



Fig. 3.18 This shows a 24 h GPS data using standard positioning and WAAS. Note how the recorded position tends to 'wander' in one direction and back towards the center, which is the 'true' position



Fig. 3.19 This shows the improvement in performance of GPS over time. (Image courtesy http://www.gps.gov website.)

Figure 3.19 shows the overall improvements in the standard positioning service since 2001, showing less than 1 m precision. Your position and navigation using GPS are determined using a standard reference model of Earth called The World Geodetic System, Version 1984 (WGS84). This is a standardized, global coordinate system used in geodesy, mapping, GPS and navigation. It includes a global coordinate system, a standard spheroid reference surface (the datum or reference ellipsoid), and a gravitational surface (the geoid) that defines sea level. The current version is called Version 1984, but it was actually last updated in 2004. This is a global datum, where the origin is the center of Earth's mass, computed to less than 2 cm precision. The datum surface is an oblate spheroid, and this unified, global datum replaces numerous regional and national datums that were mutually incompatible. The WGS84 datum is accurate worldwide and is globally consistent to within +/1 m. Your GPS receiver actually works in WGS84 but can, using software, display your position in a variety of coordinate systems such as the Universal Transverse Mercator (UTM) and others, depending on your needs and the maps you are using.

GPS Upgrades

The GPS system provides excellent capabilities but is still essentially a 1970's design, so a major upgrade is underway that will provide significant improvements into the future. In 2010 Boeing was selected to develop and manufacture a new generation of GPS satellites that will provide higher accuracy, improved atomic clocks, longer satellite life, and re-programmable onboard processors. In 2014 Lockheed-Martin won the contract for the new Block III satellites that will have a second civilian code, improved anti-jamming capabilities, a stronger signal, more power, a new military code, and a completely upgraded ground control segment. A second civilian signal "L2C" is designed to meet commercial GPS user needs and is located at 1227 MHz. This will allow automatic ionospheric correction between it and the L1 signal, which will significantly improve positioning accuracy, as the state of the ionosphere is the single major source of error in our GPS error budget. It will also broadcast with higher power, improving reception under tree canopies and in restricted areas, even indoors. The U. S. Commerce Department estimates this alone could generate an additional US\$5.8 billion in economic benefit through 2030. A third civilian signal, L5, is designed to meet vital safety-of-life transportation and related needs. It is broadcast in a band reserved for aviation safety services and features higher power, greater bandwidth and advanced signal structure. Consumers can use L5 along with L1 to improve aviation, rail, water and highway safety and signal access. Research underway shows that using a new technique called tri-laning, or use of these three civilian signals, may provide sub-meter precision without the use of augmentation systems.



Fig. 3.20 New GPS block IIIA satellite. (Image courtesy of the U. S. Air Force.)



Fig. 3.21 Improved ground control segment for the upgraded GPS system. (Image courtesy of www.gps.gov.)

Fig. 3.22 Glonass image courtesy Glonass



The new system is referred to as GPS III, and the plan is to acquire at least 32 new Block IIIA satellites. The satellites will also contain laser reflectors for improved orbital determination, already a feature with Glonass and a feature to be included in Galileo (Fig. 3.20).

A new military code, called the M-code is also under development for use by 2016. The new M-code is completely autonomous. In contrast, the existing P-code usually requires acquisition of the C/A code first. New Block IIR-M satellites will also have a spot beam that can saturate a given area several hundred km wide with a much stronger signal to overcome jamming and spoofing, which are discussed below.

In 2008 the U. S. Air Force awarded a contract to Raytheon to create a nextgeneration operational control system for GPS. This will add new capabilities to the control segment, including controlling the new satellite signals.

The U. S. government has committed to operating the GPS system for the foreseeable future. One major change will be to eventually adopt the three-orbital plane configuration of Glonass and Galileo instead of six, allowing multiple satellites to be launched at a time, and thus reducing launch costs (Figs. 3.21 and 3.22).

The next-generation GPS system will also include the Distress Alerting Satellite System (DASS), to provide improved and redundant Cospas-Sarsat capability to all medium-Earth orbit (MEO) navigation satellites.

Glonass

The Russian Glonass system ("GLObalnaya NAvigatsionnaya Sputnikovaya Sistema," or GLObal NAvigation Satellite System) was begun in 1976, with the first satellite launch in 1982. It was declared operational in 1990 but did not have a complete constellation until 1996. It is operated by the Ministry of Defense of the Russian Federation and is similar in design and operation to the U. S. GPS system but with some design differences. It is the largest project of the Russian Federal Space Agency and has consumed a large portion of its budget over recent years. The 24 satellites are in three 19,130 km orbits spaced 120° apart, with a 64.8° inclination to the equator. The inclination is higher due



Fig. 3.23 The Russian Glonass space segment with three orbital planes and a Glonass-M satellite. (Image courtesy of Glonass.)

to the northern location of the Russian landmass. The satellites are launched three at a time on Proton launchers. Each satellite has a 17 day ground repeat pattern. Glonass also transmits a C/A on L1 and P-code on L1 and L2, and uses a frequency division multiple access (FDMA) technology, unlike GPS, which uses a code division multiple access (CDMA) technology. Another difference is that Glonass uses a Russian-developed PZ-90 global reference system, which is slightly different from the WGS84 used by GPS, and Russia also has its own atomic time reference system (Fig. 3.23).

The Glonass system suffered with the demise of the Soviet Union, and the constellation was down to only six working satellites in 2000, making the system no longer operational. Russian President Putin put an emphasis on the restoration of the system, and by 2011 the system was fully restored. In 2007 all restrictions on the system were lifted, and the system was made available for civilian use, while still maintaining an encrypted military component. There have been two Proton launch failures, each with three satellites, but the constellation is currently fully maintained. In 2014 there were two unexpected Glonass system-wide outages. On April 2, 2014, there was a system-wide failure of the Glonass constellation, which lasted more than 10 h. This was reportedly caused by erroneous data being uploaded to the satellite ephemeris data. The constellation was slowly restored, as controllers had to wait until each satellite came into view of a control station on Russian territory for the new data to be uploaded. The same thing occurred again on April 15, with eight satellites going offline (Fig. 3.24).

The control segment is entirely located within the Russian landmass, with the ground control and time reference centers located in Moscow. Four tracking and telemetry stations are spread across Russia, with external Glonass control stations in Brazil, Antarctica and soon in Nicaragua. The U. S. Congress in 2014 denied a Russian request to place one in the United States, so Russia responded by ordering all GNSS reference stations in Russia to restrict their data distribution.



Fig. 3.24 A Russian military dual Glonass/GPS receiver. (Image courtesy of Glonass.)



Fig. 3.25 This shows the number of Glonass satellites in operation. (Image courtesy of Glonass.)

As noted earlier a number of smartphone models contain dual GPS and Glonass receivers, providing increased accuracy, quicker position fixes, and better satellite geometry (Fig. 3.25).

Russia is undertaking a major upgrade of the system, similar to the current GPS III modernization. This will include additional frequencies and increased power and will make the system more compatible with GPS and Galileo as well as provide better precision. It will also include also a MEOSAR capability like the U. S. DASS system (Fig. 3.26).



Fig. 3.26 Glonass modernization process. (Image courtesy of USCG.)

The Compass/Biedou System

China has developed its own, independent GNSS system, in operation since 1999. It had originally been invited to participate in the European Galileo system as a partner, and participated in early activities, but this arrangement did not work out, and China was dropped from Galileo by Europe. As a result, China decided to rapidly pursue its own system, and, in fact, Beidou will become fully operational well before the European Galileo system. Limited capability has been available since 2000 (Fig. 3.27).

The first Chinese system was called Beidou (or the Big Dipper constellation, used for finding the Pole Star for navigating), and consists of three satellites operating since 2000. This design was different from the GPS, in that it was a two-way configuration like Argos, with the satellites communicating with the user terminals and the possibility of transmitting SMS data to user terminals. This design provides text message capability, but also limits the total number of concurrent users.

Fig. 3.27 The first Chinese Beidou I user segment and hand-held receiver. (Image courtesy of Beidou.)





Fig. 3.28 Chinese Beidou system regional satellite coverage. (Image courtesy of eoportal.org.)

The second-generation Chinese system, originally called Compass, but now called Beidou II, will consist of 35 satellites and has achieved initial operational capability in the Chinese region in 2011. The current system is made up of 14 satellites: 5 GEO, 4 MEO and 5 highly inclined GEO satellites (as of 2014), which provides regional capability for China (Fig. 3.28).

When completed, the space segment will consist of 5 GEO satellites, 27 MEO and 3 inclined GEO satellites, for a total of 35 satellites providing true global coverage. The MEO satellites are in three equally spaced 21,150 km orbits, inclined 55.5°. The system was originally to be completed in 2020, but development has been accelerated, and it is now to be completed by 2017. The frequencies are overlapping with the European Galileo system, and the first to launch and operate will have primary use of the frequency under ITU policies. One unique feature of the Beidou design is that they have the SBAS augmentation capability (like the WAAS described below) built into the system as an integral part, rather than operating as a separate augmentation capability. Beidou II MEO and inclined GEO satellites transmit a D1 message and the GEO component satellites transmit a separate D2 message, which also includes the augmentation service data. The fully deployed system will have a free commercial service and a restricted service for Chinese government users.

Galileo

Ever since the success of the U. S. GPS system, both commercially and politically in terms of a new space system, Europe has been very uncomfortable with relying on what is basically an American military system. As the commercial markets

Fig. 3.29 The Galileo logo



grew, European nations decided that they must become a player in this new domain. Major drivers have been European sovereignty and military independence, industrial policy and technology competitiveness, employment, launch services, as well as emerging commercial markets. The system was approached in two phases, first creating the GPS augmentation system EGNOS (discussed below), and then creating their own system called Galileo (Fig. 3.29).

The development of the Galileo system has been protracted and difficult. This was partly due to the complexity of ESA and EU processes and internal national interests, and also partly due to budgetary limitations. A major launch failure in 2014 also has slowed the process. European nations first authorized some €80 million in 1999 for system definition, and some €3.4 billion to start construction, which was not sufficient to complete and launch the constellation or operate the ground system. These funds were taken from existing agriculture and EU administrative budgets after much political fighting. Ongoing operation costs are estimated at €600 million per year, and ongoing replenishment costs are not yet available, so Europe has faced a very difficult political and financial challenge.

How do you compete with a U. S. GPS system that has been provided free of charge for over 20 years, and that meets most user requirements? This has been the challenge of Galileo. The program was started originally by ESA, but has now been taken over by the EU, and the EU is now the owner of all assets and will lead and fund the program. The original plan was for private investors and European companies to invest up to two-thirds of the system costs, but this failed to materialize, and in 2006 the EU decided to assume ownership and control. Overall lifetime costs are likely to run to over \notin 20 billion (like GPS), and it is uncertain where these funds will come from. China was originally invited to be a partner in 2003, and was to invest over \notin 230 million; several other nations also joined the program, including Israel, but this fell apart and China was un-invited, without a return of its over \notin 2 million invested so far. This caused China to decide to pursue its own Beidou system, which will be operational before Galileo.

Galileo is designed to be independent but interoperable with GPS and Glonass, and will consist of 30 MEO satellites in three evenly spaced orbital planes at 56 $^{\circ}$ inclination, with an altitude of 23,222 km. Each satellite will have two rubidium atomic clocks and two passive hydrogen maser atomic clocks, and the system will operate much like GPS and Glonass.

The completed system will offer five levels of service:

- Galileo Open Service (GOS) an open access, ~6 m position and time signal.
- Galileo Commercial Service (CS), a fee-based subscription service with guaranteed access to two additional encrypted signals and improved precision.
- Galileo safety-of-life (SoL) open access service, designed for critical aviation and marine navigation.
- a MEOSAR search and rescue capability (like the DASS system)
- Galileo Public Regulated Service (PRS), an encrypted security and military code that can remain operating if other services are disabled in a crisis.

The first satellite was a place-holder to maintain the ITU-awarded frequency, launched in April of 2008, named GIOVE (Galileo In-Orbit Validation Element). This was the first use in space of a passive hydrogen maser clock, which will be at the heart of the Galileo design. Four operational design satellites were launched in October of 2011 and 2012, launched from ESA's spaceport in Guyana on a Soyuz launcher with a Frigat upper stage. These four initial satellites allowed the system to be tested from the ground.

A 2014 launch of two more satellites failed, after the Frigat upper stage left them in an incorrect orbit, but two more satellites were successfully launched in 2015. Plans are for later launches to be done in groups of three on an Ariane 5 or Ariane 6. Complete, global coverage is not expected before 2020 and may be delayed beyond that. The long-term financial structure and funding for the system is still uncertain, and there is discussion in Europe to mandate the use of Galileo receivers for certain uses in Europe, to provide a user market and funding, but this will be a contentious political decision both within Europe and between Europe and the United States and would also involve the World Trade Organization.

The Galileo headquarters will be located in Prague, Czech Republic, which will be the home of the European GNSS Supervisory Authority (GSA). There will be two ground operations centers located in Munich, Germany, and Fucino, Italy.

The Indian Regional Navigation Satellite System (INRSS)

Once China decided to operate their own Beidou GNSS system, India's government approved the development of an independent GNSS system in 2006, with a commitment to operate a regional Asian system, not a global system. The program was developed by ISRO, the Indian Space Research Organization. INRSS

Fig. 3.30 The IRNSS-1A navigation satellite. (Image courtesy of ISRO.)





Fig. 3.31 IRNSS space segment configuration. (Image courtesy of ISRO.)

will consist of a 7-satellite constellation, with 3 GEO and 4 highly elliptical orbit (HEO) satellites. The INRSS satellites will have rubidium atomic clocks (Fig. 3.30).

The ground segment will consist of an ISRO Navigation Center, 21 ranging and monitoring sites located around India, a network timing center, several laser ranging stations to do orbit determination, and two master control stations (MCCs). Like GPS, it will have an open civilian signal and an encrypted restricted service for use by the Indian military. Five satellites have been launched as of 2014, and the constellation should be completed with the final two launches in 2016. It is planned that all aspects of the system will be designed and constructed in India, and the satellites will all be launched by Indian rockets. India also plans to create its own standardized timing system. The GAGAN (discussed below) is an integrated aspect of the design, providing wide area augmentation throughout the Indian region using the same GEO satellites (Fig. 3.31).

The Quasi-Zenith System

Japan has developed a unique GNSS augmentation system called the Japan Quazi-Zenith Satellite System (QZSS). Japan has the world's most dense use of GPS data for car navigation and other services. This QZSS system is designed to address the problems inherent in using GPS in dense urban areas such as Tokyo and other Japanese cities. In urban landscapes, large buildings reflect the incoming GPS signals and create what is called "multi path interference". As these reflected signals



Fig. 3.32 The Japanese QZSS augmentation system. (Image courtesy JAXA.)

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Fig. 3.33 This shows the first page of Trimble's GNSS Planning Online page, with the options to pick your location, height, date and time. The author used the map option to choose my building at the University of North Carolina at Chapel Hill. Once these are set, you can choose which GNSS constellation (or individual satellites) to view using the Satellite library tab, which uses the current downloaded data. (Image courtesy of http://www.Trimble.com.)

travel farther, they create errors in the position. The QZSS system consists of three equally spaced satellites in very highly inclined (at a 45° angle to the equator) geosynchronous orbit at an altitude of 35,786 km and with a period of 24 h. These satellites trace out a 'figure 8' pattern over the ground, with one of the three satellites always being high enough over Japan to be nearly vertical, thus allowing good signal reception in the urban canyons of Tokyo and other major cities.



Fig. 3.34 This shows the World View option of all satellites in view, and the relative elevation of all satellites in view. (Image courtesy of http://www.Trimble.com.)



Fig. 3.35 This shows the total number of satellites in view, and the skyplot of their locations over the chosen 6 h period. (Image courtesy of http://www.Trimble.com.)



Fig. 3.36 This shows the Dilution of Precision (DOP) and individual satellite visibility. (Image courtesy of http://www.Trimble.com.)

The system was started in 2002, with its first launch in 2010, and was completed in 2013. It is designed to be fully interoperable with both the GPS and Galileo signals for redundancy and reliability, and it works by transmitting signals compatible with the GPS L1C/A signal that provide ranging correction of the GPS



Fig. 3.37 Finally, this shows the state of the ionosphere in total electron count and scintillation. (Image courtesy of http://www.Trimble.com.)

signal. It also provides system health data. QZSS also has an innovative timekeeping system that does not require atomic clocks on the satellite, reducing the cost and complexity of the satellites. This innovative system also provides mobile satellite communications in addition to PNT services (Fig. 3.32).

So the current situation is that we will soon have five operational GNSS systems, the U.S. GPS III, Russian Glonass, Chinese Beidou II, European Galileo, and Indian IRSS (regional) systems. The civilian component of these provide multiple interoperable signals providing precision positioning, navigation and timing worldwide.

An excellent way to visualize all of these systems, and also to keep updated on their ever-changing status, is to use the free online GNSS planning software from Trimble (http://www.trimble.com/GNSSPlanningOnline). This simple program allows you to pick your location, date and time, and to visualize many aspects of the GNSS satellite status in that time range (Figs. 3.33, 3.34, 3.35, 3.36 and 3.37).

Chapter 4 Aided and Augmentation Systems and Differential GPS

The civilian GPS system was intentionally developed at first with limited precision, and so later several systems were developed to improve the quality and reliability of this and the other civilian systems. Some are ground-based and others are spacebased. These use a technique referred to as differential GPS, or DGPS. These were originally developed to defeat selective availability, and to provide higher precision in applications such as civil aviation that require both higher precision as well as system integrity not provided in the basic signals.

How Differential GPS Works

DGPS uses a fixed reference station whose position has been surveyed with high accuracy. The GPS signal received is compared with the actual known position, and the difference is computed and transmitted in near real-time by low-frequency radio to other GPS receivers in the area every second. This brings the precision of the location from 15–30 m to 3–5 m or better. Many GPS receivers now have the ability to receive on this second frequency, but many also use a separate, dedicated receiver. The correction is best close to the DGPS reference station, and provides well less than 1 m precision at the reference station, but DGPS can still be used effectively up to a distance as far away as 400 km (Fig. 4.1).

Ground-based Augmentation Systems

The U. S. government is committed to continuing to provide GPS to the civilian community for the foreseeable future, at a minimum standard positioning service performance standard. This standard is stated to be a worst case of 7.8 m 95 % of the time. In practice, the actual accuracy depends on many variables, including



receiver quality, atmospheric and ionospheric conditions, and blockage due to buildings and terrain, but it is often much better than this minimum standard. This accuracy is augmented in the United States by the nationwide differential GPS system (NDGPS), a ground-based augmentation system that also provides system integrity data. These broadcast a local correction signal around a limited geographical area. Some 50 countries around the world operate similar systems to a common international standard for interoperability. The U. S. system can be used in real time, or data collected in the field can be post-processed.

In the United States, the Coast Guard began establishing a network of differential GPS beacons along the coast and at major ports, using existing but obsolete directional radio beacons in the 275–325 kHz band. This system was designed for coastal and port navigation, and the coastal DGPS system was so successful that the Department of Transportation and U. S. Coast Guard have expanded the USCG maritime differential GPS system (MSGPS) into a nationwide differential system called the national differential global positioning system (NDGPS) program, which has been operational since 1999. This system provides real-time broadcast of differential corrections to improve the overall reliability and accuracy of GPS signals using a network of fixed stations, called reference stations. The sites are owned by the Department of Transportation, but are managed by the Coast Guard. Over 92 % of the lower 48 states have single coverage, and 60 % have dual coverage. These stations also monitor the GPS satellites for errors, and can broadcast a warning not to use a given satellite that is not working correctly.

As you can see in Fig. 4.2 above, Canada also operates a similar system.



Fig. 4.2 This shows the NDGPS network. *Purple areas* have coverage of at least two reference signals, *blue* have one. (Image courtesy of the U. S. Coast Guard: http://www.navcen.uscg.gov/images/Plots/Canadian_DGPS_MAY13_Lg.jpg.)

The entire NDGPS network also acquires water vapor data for NOAA and also is used for tectonic plate movement analysis and earthquake warnings, in partnership with the University Navstar consortium.

There are many other governmental and private sector DGPS networks around the world. Although these provide real-time correction, there are also many systems around the world that provide post-processing of GPS data. This can be done days or months after the data were collected in order to achieve even higher precision. The National Geodetic Survey of NOAA coordinates a network of continuously operating reference stations (CORS) that provide both carrier phase and code-based measurements for post-processing of GPS data throughout the United States and its territories. A wide range of scientific, surveying and GIS users take advantage of the system at no cost. As of January, 2014, there were over 1,900 CORS stations, supported by over 200 governmental, academic and private organizations. The NDGPS system provides five categories of services:

- 1 m code-based real-time data
- 10–15 cm real-time high accuracy data
- to 3 cm post-processing of data
- 2–3 mm stationary scientific measurements for plate tectonics and earthquake warning
- water vapor data for weather forecasting to the National Weather Service of NOAA.



Fig. 4.3 CORS stations. (Image courtesy of NGS NOAA: http://www.ngs.noaa.gov/CORS_Map/.)

Future plans include a national, 3-D, dynamic, real-time service with 15 cm accuracy at a 240 km (150 mi) distance on a dynamic platform such as a boat or train, and less than 2 s of warning for satellite errors (Fig. 4.3).

The CORS network is accessible at http://www.ngs.noaa.gov/CORS_Map/. GPS correction data can be downloaded remotely around the clock. The NDGPS system was designed to be an international and non-proprietary standard, and the data and signal are free to all users.

International DGPS Networks

Over 50 nations around the world also operate similar systems, creating an international, seamless precision coastal and (incomplete) land navigation enhancement system (Fig. 4.4).

Although ground-based correction systems using DGPS are very useful, they cannot be utilized for much of the world, and are not useful for international aviation and marine requirements. For this, space-based augmentation systems (SBAS) have been developed.



Fig. 4.4 International DGPS systems. (Image courtesy of the U. S. Federal Railway Administration.)

Space-based Augmentation Systems

WAAS (United States)

Over broader areas of North America, the satellite-based wide area augmentation system (WAAS) provides continental-scale and real time augmentation. WAAS was developed to provide highly accurate navigation primarily for commercial aircraft, but the system also works well for hand-held receivers on the ground. This was developed because the standard civilian GPS signal does not meet FAA aviation requirements for accuracy, integrity and availability. This system was activated in 2003 and provides differential correction over broad areas with accuracies to less than 3 m precision 95 % of the time.

There are 38 ground reference stations, with twenty in the continental United States, five in Mexico, four in Canada, seven in Alaska, one in Hawaii and one in Puerto Rico. Three master control stations determine the regional offset, which is then uplinked through four ground uplink stations (GUS) and broadcast through two commercial geostationary satellites to aircraft (or ground receivers) throughout North America. The cost of the system is some US\$50 million per year, but the current ground instrument landing system costs over US\$80 million in maintenance alone. The service is provided free of cost (Figs. 4.5 and 4.6).

The WAAS system operates in North America, as shown in Fig. 4.7. The coverage area extends well into South America and the Atlantic and Pacific oceans.

There are several compatible international systems, including the European Geostationary Navigation Overlay Service (EGNOS), the Japanese Multi-functional Transport Satellite (MTSAT)-based Satellite Augmentation System (MSAS), the Russian SDCM (System for Differential Corrections and Monitoring) system



Fig. 4.5 The WAAS system uses commercial telecommunication satellites to broadcast augmentation services for the GPS constellation. (Image courtesy of the FAA.)



Fig. 4.6 The footprint of the WAAS augmentation signal. (Image courtesy of the FAA.)

and the Indian GPS And Geo-Augmented Navigation (GAGAN) system. China's Beidou includes this capability within its basic design and does not require a separate augmentation system. Many inexpensive hand-held GPS receivers are WAAS-enabled for increased accuracy.


Fig. 4.7 This shows the coverage of WAAS, EGNOS, GAGAN, MSAS, etc. It also shows the commercial telecom satellites that broadcast the correction signals. Note the lack of coverage in South America and Africa

EGNOS

The European counterpart of the WAAS system is the European Geostationary Navigation Overlay Service (EGNOS), which was jointly developed by the European Space Agency (ESA), the European Union (EU) and EUROCONTROL (air traffic control), and has been operational since 2009. It is designed to augment and complement GPS and other systems, and consists of 4 geostationary satellites, 34 ground control stations called Ranging and Integrity Monitoring Stations (RIMS), and 6 Navigation Land Earth Stations (NLES) that broadcast the data up to the satellites. Four Mission Control Centers (MCCs) manage the system in Spain, Italy, England and Germany. The system is operated by the private company known as the European Satellite Services Provider. The EGNOS coverage almost extends to meet the WAAS coverage area over the north Atlantic, and extends to cover the Mediterranean and extreme northern Africa. There are some plans to extend coverage into Africa, but this is not yet available. There is reduced ability to use the system on the ground and in urban areas. These limitations are largely due to issues involving the high northern latitude regions and viewing angles to the GEO satellites (Fig. 4.8).

GAGAN (India) India operates the GPS-Aided GEO Augmented Navigation system, with 15 reference stations, three control stations, three uplink stations, and three GEO satellites. The project is overseen by the Airport Authority of India and ISRO, the Indian Space Research Agency, and was first operational in 2008. Raytheon Corporation built the system. (http://india.gnss.asia/node/67).



Fig. 4.8 EGNOS ground network stations. (Image courtesy WikiCommons)

MSAS

The Japanese Multi-functional Satellite Augmentation System (MSAS) was commissioned in 2007 using two GEO satellites. It is designed and is operated by the Ministry of Land, Infrastructure and Transport and the Japan Civil Aviation Bureau to work with both GPS and follow-on systems and improves the position down to about 2 m in both vertical and horizontal dimensions. It uses the MTSAT-1R and two GEO satellites located at 140 and 145°.

SDCM

Russia is developing the System for Differential Corrections and Monitoring (SDCM) as a component of its GLONASS system. This is somewhat different from the others, in that it will provide integrity monitoring for both the GLONASS and U. S. GPS system, whereas the others, at present, only work with GPS. Due to the size of Russia, there are a total of 19 reference sites in Russia as well as five international ones, and three GEO satellites for broadcast. It achieved partial operational status in 2011.

China has taken a different approach, in that the augmentation coverage is an inherent part of the Beidou II design and will be broadcast from the GEO satellites that are a part of the Beidou system. So there will be no separate Beidou augmentation system; it will be designed into the overall system.

Together, these systems provide continental-scale GPS correction to less than 2 m, as well and integrity information, but the southern hemisphere is largely not covered, and this is a major limitation to be addressed in the future.

There is a separate U. S. military SBAS system, the Wide Area GPS Enhancement (WAGE) system. This is only available to encrypted P(Y) code receivers and functions much like the other systems described above. This system is only for U. S. military users.

Kinematics Versus Carrier Phase GPS

All previous discussion on how GPS works relates to code-based GPS. There is another technique, called carrier phase or kinematic GPS, that works in a fundamentally different way and which also provides the highest precision. This does not use the code-based process described above, but works as an electronic distance measurement system that records the exact number of 17 cm carrier cycles between the satellite and receiver on the ground after the modulation is removed from the carrier. This provides a location within 1 mm plus 1 part per million of the base length, and gives a fixed base station and multiple mobile units a position accurate to millimeters on the ground. Most systems start with the code-based signal, and then measure the carrier wave, which is broadcast at 1575.42 MHz, on a wavelength of 17 cm.

At least two receivers are used, within 30 km of each other, the carrier phase is tracked by both, and the difference in phase is measured. Being able to measure the exact phase of this accurately gives us 3–5 cm positioning in real time, and 1–3 cm with post-processing. This has revolutionized the surveying profession and cadastral mapping, and is used in the measuring of continental plate tectonics, volcano deformation, and more. These systems are more expensive than code-based GPS receivers, often costing from US\$5,000 to \$50,000. Real-time kinematic systems provide centimetric relative positioning for precision applications such as civil engineering, construction and agriculture. This is also referred to as carrier-phase enhancement, or CPGPS, and uses a fixed base station and multiple mobile

Fig. 4.9 Carrier phase tracking. (Image courtesy of the U. S. GPS.)



CARRIER PHASE TRACKING





receivers. The base station broadcasts the carrier phase, and the mobile units compare their phase measurement with that of the base station. Accuracy of 1-2 cm is possible (Figs. 4.9 and 4.10).

GNSS Markets, Trends and Major Players

A European commission report recently predicted that GNSS and related businesses will account for 140 billion Euros in applications and hardware by 2015.

As of 2010, over 40 million GPS units have been delivered, with sales of ~60,000 dedicated GPS units sold per month. This does not include all of the millions of smartphones sold each year, and the rate continues to increase. The development of Russian, Chinese, European and Indian systems will also cause large new sales in these markets. In 2010, the economic value of GPS-related services exceeded US\$50 billion per year, with a steady increase projected to reach over US\$100 billion in 2015, according to the University of Washington Olympic Natural Resources Center. According to a research report "World GPS Market Forecast to 2013," it was projected that shipment of GPS devices will grow at a rate of more than 20 %. (http://www.reportlinker.com/p0116472/World-GPS-Market-Forecast-to.html) (Figs. 4.11, 4.12 and 4.13).

Despite the massive growth of smartphones with GNSS chips, the portable GPS receiver market is estimated to reach US\$7 billion in 2018, according to an ABI, Research's quarterly GNSS database forecast. (http://gpsworld.com/dedicated-gps-devices-to-reach-7-billion-in-2018/) (Figs. 4.14 and 4.15).

A marketing study published by MarketsandMarkets in 2013 determined that the total GPS market is expected to reach \$26.67 billion by 2016. (http://www.mar ketsandmarkets.com/PressReleases/gps.asp.)

And a Raytheon study shows a total of US\$39.6 billion dollars of annual U. S. GPS equipment sales and some 3.3 million U. S. GPS-related jobs in 2012.





Fig. 4.11 This charts shows the explosive growth of worldwide GPS sales from 1993 to 2003. This growth continued over the next decade and shows no sign of stopping



Fig. 4.12 This chart shows the relative size of the individual GPS markets. What is particularly interesting is that the military market is relatively quite small (shown at the *top*), and decreases, while the car navigation market grows but eventually becomes less dominant relative to other applications



Worldwide GPS Revenues (by Market Segment)

Fig. 4.13 This chart shows the worldwide GPS revenue by market segment from 1993 to 2003. The tremendous grown is evident, and, again, the military market is quite small and growing smaller. There is a huge and across-the-board increase in many of the major commercial markets. The military market is again is relatively quite small and consistent, as is the marine and aviation markets. Surveying and GIS, machine control, consumer and car navigation markets all show very large growth



Fig. 4.14 This shows the U. S. GPS manufacturer market in 2008. (Image courtesy of http://www.gpsmagazine.com.)



Fig. 4.15 In Europe, the Dutch company TomTom has the largest share. (Image courtesy of http://www.gpsmagazine.com.)



Installed base of GNSS devices by region

Fig. 4.16 GNSS growth estimates by region. (Image courtesy of the European GSA.) (http://www.blackroc-technology.com/technologies/gnss/market.)

GNSS Market Report

The European GNSS Agency released a market report in 2013 (its third) that predicts an installed base of over 7 billion GNSS devices by 2022, with global revenues to increase by 9 % per year through 2016 and 5 % through 2020, reaching a total market impact (i.e., equipment and related services) of some €350 billion (US\$478 b) per year in 2022. Smartphones will make up nearly half of this total market, with locations-based services growing from €150 mil to over €800 million over the next 5 years. (http://www.gnss.asia/sites/gnss.asia/files/GNSS_Market%20Report_2013.pdf) (Fig. 4.16).

Chapter 5 Applications of PNT Systems

The tremendous growth in this industry is driven by the enormous number of applications provided by GPS and the other GNSS systems. These are far beyond what was originally designed and envisioned to be a strictly U. S. military system. Providing extremely precise, three-dimensional timing and navigation in a worldwide common grid that can be easily converted to any local mapping coordinate system has created huge new commercial markets and new scientific and public benefits. GNSS allows for continuous, passive, all-weather operation of an unlimited number of users anywhere on Earth, up to low-Earth orbit. But we cannot deny that GPS is vital to national security needs, and GPS is an aspect of almost every U. S. military activity. It is the same for Glonass and the Russian Federation, and will be so for China, India, Japan, and the EU.

First and foremost, before the other amazing applications, GNSS was designed as a military timing, positioning and navigation system, and it is used for this purpose every hour of every day around the world. Even artillery shells now have GPS receivers, and every military vehicle, ship, drone, and airplane now relies on GPS. In fact, the dependence of U. S. military operations on GPS has led to concern about what would happen if access to the system was somehow denied in time of crisis, or if a major solar storm should knock out space-based GNSS satellite networks (Fig. 5.1).

Aviation Ground-based Augmentation

For precision aviation approach and landing, local or ground-based augmentation systems have been developed. These use the GPS constellation, but augment the precision by using local, ground-based pseudolites, or signals broadcast from the



Fig. 5.1 The various applications of GNSS for timing and navigation. (Image courtesy of www.gps.gov.)

airport that simulate additional, local GPS satellites. These will provide for precision approach, departure, taxi, and CAT I, II and III approaches in any weather. It also allows for an unlimited number of customized approaches through difficult terrain, avoiding noise-sensitive areas, mountains and other hazards, while reducing the cost of existing ground-based navigation systems (Fig. 5.2).

The future of aviation GPS in the United States is called ADS-B, the automatic dependent surveillance and broadcast system. It is a part of the next-generation air transportation system to be in place by 2020. The design has each aircraft broadcasting automatically its position based solely on GNSS. This will be used for traffic surveillance both on the ground and in the cockpit. This system should operate at 10 % of the cost of the national network of ground radars, which require frequent maintenance and are often located in remote locations. It should be far more accurate, and will operate better over oceans and mountains. It will also provide improved pilot situational awareness and real-time traffic conflicts both in the cockpit and to controllers. The concern that comes with this new increased reliance on GNSS capabilities, however, is if something like a natural cosmic hazard or a manmade electromagnetic pulse (EMP) should interfere with the availability of PNT networks (Fig. 5.3).



Fig. 5.2 Local area augmentation system diagram



Fig. 5.3 The U. S. ADS-B system design. (Image courtesy of the FAA.)

Marine Navigation

Standard marine navigation has been revolutionized by the incorporation of GPS navigation and the development of GPS electronic navigation charts, but there are many other applications. One interesting one is the use of GPS by the U. S. Coast Guard to precisely place navigation buoys. This provides for both more precise and more efficient work, saving millions of dollars each year.

Space Navigation and Virtual Launch Ranges

One very interesting application is for satellite launch facilities to replace groundbased telemetry and tracking systems. This is similar to the ADB-S approach, and would provide reduced cost, increased availability and improved safety margins at space launch facilities such as Cape Kennedy and Vandenberg AFB, the two primary U. S. launch facilities. A recent Delta 4 launch of a GPS satellite (2014) at the Cape was tracked using GPS rather than the traditional network of RADAR systems along the launch path. United Launch Alliance's Atlas and Delta rockets are being upgraded to provide GPS metric tracking for range safety operations, rather than traditional C-band radar transponders on the vehicle. More accurate data could be available, and large amounts of ground equipment and staff costs could be saved.

The move to a "space-based launch range" improves reliability and reduces cost. Launches have had to be delayed due to ground infrastructure not being available, so this is a part of improving launch range 'responsiveness,' and GPS actually provides better position and velocity data. Two GPS receivers on the second stage use an S-band radio to send the vehicle's position and velocity. The system is supplied by Space Vector Corporation. This approach is also being used at the NASA Wallops Island and Kodiak, Alaska, launch facilities as well.

Space Applications

Spacecraft and satellites in low-Earth orbit use GPS on a routine basis. The International Space Station has several GPS systems, and these are used for position, time, and navigation, the first use of GPS for attitude control of a space vehicle. Four GPS antennas are located in a 1.5 by 3 m rectangle on the S-zero truss, a configuration capable of precisely determining vehicle attitude. The four antennas feed information through cables to two GPS receivers in the U. S. Destiny laboratory. This provides continuous ~100 m position and precise attitude data that is far better than traditional ground-based techniques that were only updated daily and with less precise such tracking for attitude control and other applications becomes. In short, this application is limited to low-Earth orbits (Fig. 5.4).



Vehicle Navigation

Vehicle navigation and control is a developing concept, and driverless cars and trucks are being developed, by Google, Apple and others, along with 'smart high-ways,' that will use GPS to automatically navigate vehicles without driver input. Localized sensors on driverless cars, however, must be used to ensure complete safety of operation. Commercial stolen vehicle systems using GPS technology are widely available today, and police use GPS to track suspects and parolees. Commercial fleet tracking systems monitor trucking and cab fleets as well as regulation compliance and deliveries.

Precision Agriculture

Precision Agriculture is the integration of PNT, remote sensing, GIS, and ancillary weather and historical crop production data. It uses high resolution GNSS in the cab of the tractor within a GIS screen. It automatically drives the vehicle and delivers different amounts of water, fertilizer, seed and pesticides for each square meter of a field, rather than for an entire field, using a computer-based variable rate application software. This can be based on analysis of previous yield, which can be collected by Precision Agriculture devices at harvest, to determine the yield per square meter, as well as soil analysis and remote-sensing imagery collected during each phase of the growing season, allowing reduced application amounts, lower cost, less pollution, and higher yields. Automatic tractor guidance allows for working at night or in low visibility conditions. There is great potential for improving the environmental impact and sustainability of agriculture worldwide by using Precision Agriculture, despite its initial cost. Several commercial systems are available and in use today (Fig. 5.5).

Fig. 5.5 GPS being used for precision agriculture. (Image courtesy of www.gps.gov.)



Timing-Banks, Stock Markets and Precise Scientific Time

GPS and other GNSS systems really are very precise timing devices that allow us to determine our position and navigate. The current generation of GPS provides timing with a precision on the order of ~40 ns, and the future architecture will provide ~1 ns. GPS provides atomic clock precision anywhere on the planet *without* the need to have expensive atomic clocks at each location. Synchronizing complex communications systems, financial networks, and power grids is now a standard GPS application. Any transaction that benefits from a time stamp can use GPS, and various scientific applications, where divergent locations need to time their observations precisely, all use GPS. Some applications are in astronomy, where time stamps record individual observations, and particle physics experiments, where precise timing is critical.

There are many applications that rely upon the precise timing signal from space for a variety of important applications, and there are currently over 1 million dedicated GPS timing receivers in use around the world that are not used for navigation at all. There are over 500,000 cell-based telecommunications stations around the world that use GPS to synchronize their networks. Many science experiments, including the Very Large Baseline Array and experiments in astronomy and particle physics rely on GPS for precision timing. Electrical power grids synchronize the current across the grid using GPS, and the global banking and stock markets also use GPS to time stamp transactions each day. Every email packet sent across the Internet has a GPS-derived time stamp. The number of these applications is constantly growing, and even Hollywood movie cameras use GPS timing to edit film acquired by several cameras at the same time. Weather radar is synchronized using GPS, and wireless telephone and data networks all manage their base station networks using GPS time.

Military Applications

The original purpose of GPS was as a military system, and GPS and all the other systems are routinely used for land, sea and air navigation and positioning. Missiles and individual artillery rounds now have GPS or similar receivers to navigate them to their targets.

Scientific Applications

Geological scientists use precise GPS systems routinely around the world to measure plate tectonics, volcano bulging, ecological monitoring, ground trothing of remote-sensing imagery, and other geophysical events.

Geodesy, Surveying and Mapping

Surveying and mapping have been revolutionized with the development of RTK and carrier-based GPS. Surveyors and mappers now routinely use these precise systems to map our world.

Atmospheric and Ionospheric Science

GPS has revolutionized our understanding of the ionosphere. Because the ionosphere alters the GPS signal, we can use GPS to accurately measure the state of the ionosphere on a global and continuous basis (Fig. 5.6).

Location-based services is a new application tied to the development of smartphones such as the Apple iPhone. It uses the GPS and Glonass receiver in your phone to track your position and to provide you with information about stores, sales and other commercial opportunities in your immediate area. This is a major new commercial market, but also has personal privacy implications.

Civil Engineering

GPS has now been incorporated into a variety of civil engineering applications, including continuous analysis of structural deformation of bridges and the incorporation of CAD data directly into construction equipment. All large bridges have precision GPS receivers located on the top of their towers that constantly monitor the structure. RTK systems, accurate to a centimeter, are now included on large construction equipment and are used to sculpt construction sites precisely to the desired contours.



International GNSS Service Tracking Network

Fig. 5.6 The international GNSS service tracking network

Medical Tracking

Commercial systems are now available for tracking patients with dementia and Alzheimer's if they become lost. Several systems now combine cell phone, RF and GPS to be able to track individuals wearing monitors that can be as small as a wristwatch. Similar systems are also available for dogs and other pets.

Disaster Management

GPS has quickly become a critical component of disaster work, providing both timing and location data for search and rescue teams, damage assessment, mapping, fire mapping of hot spots, storm tracking and flood prediction, among others. A key practical use of GPS in disasters is emergency vehicle fleet management, often referred to as vehicle tracking systems. GPS can provide real-time tracking of all land vehicles, boats and aircraft and even supplies involved in the relief effort. These allow the disaster management teams to view their resources and watch the disaster response unfold. Thus they can more efficiently track and dispatch their resources and more effectively manage the overall response. These systems can also provide additional information such as engine RPM, emergency lights on or off, fuel and water supplies, etc. There are a wide variety of commercial GPS tracking systems available, and several new, open source systems as well. These generally consist of a GPS device, a transmission device (radio or cell phone), a tracking server that receives the data, and a user interface, which is often a web-based browser (Fig. 5.7). Fig. 5.7 This shows an open source real-time vehicle tracking system example. (Image provided by the author.)



GPS In-Situ Networks

We are seeing a growing number of in situ weather, river height, and other remote monitoring systems, and there will be many more of these in the future. Large networks of distributed data collection platforms can serve multiple functions, including early warning and real-time broad data collection before, during and after an event.

In 2013, NASA's Jet Propulsion Laboratory (JPL) and the Scripps Institution of Oceanography at UC San Diego announced the new GPS-based Real-Time Earthquake Analysis for Disaster Mitigation Network to provide enhanced warning for earthquakes, tsunamis and other extreme events in the Western United States. The system uses real-time data from existing GPS monitoring stations that have been upgraded with low-cost seismic and weather data sensors (Fig. 5.8).

The network will warn of earthquakes, track flash floods, and assist in damage assessment for critical infrastructure in near real time. It is based on integrating GPS, accelerometers, pressure and weather data. Such capabilities allow critical data to be collected in real time throughout a large geographical region. The key information generated in this manner can include ground motion, for example, which could provide early estimation of damage. Buildings could automatically disable elevators in earthquakes as well, as soon as a warning is received. Bridges could even detect deformations and automatically stop traffic.



Fig. 5.8 NASA JPL GPS station. (Image courtesy of NASA/JPL)

Hundreds of high-quality GPS units already located throughout California can provide both earthquake intensity as well as water vapor data, which is now constantly collected through the atmospheric distortion that water vapor causes in the GPS data, rather than through twice daily balloon launches (Fig. 5.9).

These new, upgraded systems can detect the very fast-moving 'P' waves of an earthquake, making possible automatic warnings for the later arrival of the slower but more intense 'S' waves, which do the most damage. Such systems could provide warnings of between several seconds to a few minutes, depending on the distance to the epicenter of the earthquake, and could automatically trigger warnings, notify emergency personnel, disable elevators, close bridge access, etc., throughout a large area. Existing rain gauges can now easily be equipped with Internet or microwave broadcasting, to provide real-time flood alerts in the same way.



Fig. 5.9 The location of over 500 real-time GPS monitoring stations that make up the Real-Time Earthquake Analysis for Disaster Mitigation Network. *Red areas* have the largest probability of earthquakes. (Image courtesy of the USGS.)



Fig. 5.10 This shows the GPS-created art project on the National Mall in Washington, D.C., in 2014. The *right picture* shows the portrait as viewed from the *top* of the Washington Monument. (Images courtesy of the BBC.)

GNSS Art

In October, 2014, the National Portrait Gallery in Washington, D.C., put on display a huge portrait on the national mall between the Lincoln Memorial and the World War II Memorial. International artist Jorge Rodriguez Gerada, who has done similar projects before in Belfast and Barcelona, used 10,000 pegs placed in the ground using GPS, and the pegs were then shaded with different colors using all organic material, much like a gigantic paint by the numbers (Fig. 5.10).

The above survey represents only a few of the many GNSS applications today, and the number will certainly continue to grow in the future as new improvements are made and new systems come online. The potential applications of this amazing technology are apparently endless.

Chapter 6 National and International Governmental Policy Issues

International GNSS Issues

We are soon to have four or five operational GNSS systems, and even more regional augmentation systems, so international cooperation in signal interference and frequency compatibility are of growing importance. Avoiding frequency interference is vital, partly due to the limited spectrum allocated and available, and also because of the possibility of intentional interference or jamming, due to the dual use nature of the technology.

GNSS signal compatibility is important so that multiple systems can be easily used together for improved results and also for system redundancy. Each of the GNSS system operators have, through the International Committee on GNSS (discussed below), agreed to mutual policies regarding interference and signal compatibility, in addition to several bilateral agreements between the operating states. But such cooperation is difficult to achieve and maintain in practice, and there have been, and will be, many complex issues to settle between the GNSS operating states.

GNSS systems are often grouped together into GNSS 1 systems (GPS, WAAS, EGNOS, MTSAT, GAGAN, and SNAS) and the newer GNSS 2 systems. The GNSS 1 systems are government-owned civilian (and augmentation) systems that are freely available and represent the first generation. Second-generation GNSS 2 systems include the new GPS III, Glonass, Galileo, Beidou II, Japanese QZSS and Indian systems, and their upgraded augmentation systems. These are also delivered as unencrypted signals and are interoperable, but also can include safety of life, public regulated, and value-added capabilities beyond the original GPS design and capability.

Legal Aspects of GNSS

There are a variety of laws and treaties that cover GNSS systems. The Outer Space Treaty, Liability Convention and the Vienna Convention all pertain. When GNSS and augmentation systems are used for civil aviation, the Chicago Convention of 1944 and Warsaw Convention of 1929 are relevant, as is the IMP Convention and U. N. Resolution 860(20) under maritime law. International telecommunications law governing the World Trade Organization (WTO) and the International Telecommunication Union (ITU) are also involved, as well as the national laws of each of the system providers. It is particularly important to note the following provisions related to civil aviation in ICAO document A32-19: Charter on the Rights and Obligations of States Relating to GNSS Services states (in part):

2. Every State and aircraft of all States shall have access, on a non-discriminatory basis under uniform conditions, to the use of GNSS services, including regional augmentation systems for aeronautical use within the area of coverage of such systems...

And

4. Every State providing GNSS services, including signals, or under whose jurisdiction such services are provided, shall ensure the continuity, availability, integrity, accuracy and reliability of such services, including effective arrangements to minimize the operational impact of system malfunctions or failure, and to achieve expeditions service recovery.

The ICAO Charter on GNSS of 1998 is limited to air navigation and has no binding force except in the court of global public opinion. Managing the complex international issues between the various GNSS-operating states, especially given the military dual use and economic impact of the applications, has been a difficult process, and this will not change as we move forward.

GNSS Frequencies, Overlap and Spectrum Issues

GNSS satellites are essentially very specialized telecommunications satellites, and thus must work within both the laws of physics for electromagnetic radiation and also the international telecommunications regulatory framework. The electromagnetic spectrum is a very limited and precious resource, and its use is regulated by the ITU. GNSS satellites broadcast in the L and C bands, as these have been set aside for mobile communications. The competition for frequencies is intense and growing as new technologies are developed, and new commercial markets are seeking to encroach on the GNSS frequencies. In the United States in 2013 there were serious concerns expressed about a land mobile satellite system named "Light Squared" that would have used frequencies just adjacent to those used by GPS networks in its so-called ancillary terrestrial component services. Eventually the FCC prohibited the use of these potentially interfering frequencies. This will not be the last time such issues of frequency coordination will arise.

Protecting existing frequency allocations is required, and frequency interference, both intentional and accidental, is a serious international issue. Frequency



Fig. 6.1 Frequency locations for the GPS, Galileo, IRNSS, Glonass, QZSS, SBAS and compass systems. (Image courtesy of WikiCommons.)

overlap is a complex diplomatic issue, partly because jamming of another's signal that overlaps your own frequency in a time of crisis effectively jams your own signal (Fig. 6.1).

GPS and GNSS Policies

The U. S. government's PNT policies have evolved over time as we have moved from the GPS system being the only system to a broader, international framework. As mentioned previously, the original concept for GPS was for an exclusively military system, and then with an added, but severely degraded, civilian signal. The shooting down of the Korean Airlines 747 changed all this, and President Ronald Reagan opened access to GPS to the world, while still maintaining a U. S. military-restricted capability. The development of other systems such as Glonass, Galileo and Biedou has again changed the dynamic into a multinational and multisystem context. The current U. S. policy perspective is based on the principles of compatibility, interoperability and transparency with the other GNSS systems. The United States is committed to the support of the GPS system for the foreseeable future, and is committed to a policy of free access to the civilian code, without any user fees, on a continuous and worldwide basis.

The GPS policy is that the U. S. government is not liable for lack of performance of GPS. When GPS is used as a means of aerial navigation, users do so at their own risk, and there is no legal recourse. This has led to the development of augmentation systems, and has been one of the main justifications for the development of the EU Galileo system. The GPS system is not, as is often presented, a strictly military system. It was originally developed as such, but it has evolved into a much more broad, vital national asset, which is operated by the U. S. Air Force but which is managed through a joint civil and military body established by the President. GPS policy is made at the highest level. The program is largely funded by the Department of Defense, but also receives funding from the Department of Transportation and other sources. The U. S. government is committed to international cooperation in GNSS, and seeks to ensure that other systems are interoperable but do not interfere with GPS operation, interference detection, and enforcement. It seeks to prevent hostile use through illicit jamming or other disruption. The United States no longer uses selective availability, and future satellites will no longer have this capability built into their design.

Figure 6.2 shows the organizational structure for the management of the GPS system. The President has the ultimate responsibility and authority, but operations are delegated to a National Executive Committee for space-based PNT, and an executive working group, which is jointly chaired by the departments of Defense and Transportation. NASA chairs the technical advisory board, and representatives of several involved departments and agencies participate. International issues are managed through the Department of State. The Department of Commerce, through its Office of Space Commercialization, promotes the interests of commercial GPS users, manufacturers, and service providers, and participates in discussions with other nations to promote international cooperation regarding GPS. The Department of Commerce also plays an important regulatory role, in that the National Telecommunications and



Fig. 6.2 The national space-based PNT organization structure. (Figure courtesy of the national coordination office for space-based PNT.)

Information Administration, along with the Federal Communications Commission, manages the frequency spectrum used by GPS. The Bureau of Industry and Security sets guidelines for export licensing of civilian GPS equipment.

In 2014, the U. S. government eased export regulations for commercial GPS receivers, moving high-end GPS receivers out from under the stricter control of the State Department to the Commerce Department, which had already overseen export of lower-end GPS systems. This takes civil GPS receivers off the State Department U. S. Munitions list and International Traffic in Arms Regulations (ITAR) regime, and moves them to the Commerce Control List (CCL), which should broaden export possibilities. All military-grade receivers capable of receiving the P(Y) code are still subject to ITAR restrictions and are strictly limited to authorized government users.

Galileo Policy Issues

The European Union is now the political, financial and program driver for the Galileo system, although it was originally conceived and developed by ESA. This was defined in 2008, when the EU assumed all Galileo responsibilities. Navigation is now an EU 'competence,' and not that of the individual member states. The EU is the overall program manager of Galileo, with the technical support of ESA and the GNSS Supervisory Authority.

The EU will be the owner of all Galileo and EGNOS infrastructure and will be the legal custodian of frequency rights. It will also be responsible for coordination with other national PNT system operators. The EU delegates the budget, design and procurement to ESA. There are now three functions in Galileo; the EU as the GNSS regulator, ESA as the system designer and agency responsible for procurement, and a GNSS service provider who will operate the system. There are multiple responsibilities for European organizations, including Eurocontrol as the aviation requirements agency.

One major potential issue is that the EU may require the use of Galileo receivers within the EU nations, protecting the European manufacturing and commercial business sector. Several versions of EU GNSS action plans include this as an option due to the delays in fielding the system and the entrenched (and free) GPS markets. With Galileo being the fourth system to achieve full operation, they face significant market constraints, and may mandate Galileo equipment (likely built within the EU) for a variety of European activities, including civil aviation, dangerous cargo tracking and eCall (112) emergency cell phone calls. This is a complex international issue, as the United States and Europe signed a 2004 agreement stating, in part: "The Parties agree to consult with each other before the establishment of any measures... that have the effect, directly or indirectly, of mandating the use of any civil satellite-based navigation and timing signals or services, value-added service, augmentation, or global navigation and timing equipment within its respective territory (unless the mandating of such use is expressly authorized by ICAO, or IMO)." http://www.insidegnss.com/node/3990.

Russian Policy Issues

Russia sees Glonass as a vital, national capability, and now mandates the use of Glonass systems for some uses. A decision by the Russian Ministry of Transport in 2012 mandated that Glonass or Glonass+GPS systems must be used for all civil aircraft and helicopters within the Russian Federation starting in 2018. All Russian registered aircraft, as well as commercial international aircraft operating over Russian territory, will be required to use the Russian systems and receivers. Hazardous cargo aircraft must comply by January 2015. Ground vehicles shipping hazardous cargo will also have to use these systems. Russia has also threatened to block imports of cell phones and other electronic devices that do not also include Glonass systems as well as GPS, and requiring Russian-made content in devices sold in Russian markets. The Russian government has decreed that all spacecraft, commercial aircraft, commercial river and ocean vessels, railways, hazardous materials shippers, surveying equipment and timing devices in Russia shall use the Glonass system.

In 2014 there was a diplomatic dustup between the United States and Russia over ground stations. Russia wanted to locate a Glonass reference station in the United States and had allowed the United States to place 11 ground reference systems within the Russian Federation, which were operated by the Russian Academy of Sciences' geophysical service as part of a global scientific effort. However, due to the crisis in Ukraine, the United States refused permission, and Russia has stopped providing data from these 11 sites until further notice. Cuba has since agreed to host the Glonass reference site. Another interesting policy issue with Glonass was that radio astronomers discovered that the system's L1 band is in the same location as the emission band of extra-solar hydroxyl molecules, and that the Glonass constellation was interfering with radio astronomers around the world. Efforts were made to minimize this problem in later satellite designs.

Chinese and Indian Policy Issues

China has pursued its own course with focus and significant resources. After its brief involvement with Galileo, China quickly developed its own system as a national priority with both military and commercial goals. A blueprint, approved by the Chinese government in 2012, envisioned Beidou capturing 60 % of the estimated US\$ 65 billion GNSS market within China by 2020. It also announced that 40 % of the system's use would be for the Chinese military. "The era of China relying on a foreign satellite navigation system is in the past," a Xinhua press release has stated. "The era of China's Beidou has arrived."

India has pursued a policy of using only India-developed technologies for the IRNSS system. All aspects of the system are developed within India, including the satellites, launch services, operation and control.

Fig. 6.3 ICGNSS



International Organizations and PNT Coordination

In 2005, the U. N.'s International Meeting for the Establishment of the International Committee on Global Navigation Satellite Systems was held in Vienna, Austria. This grew out of UNISPACE III, or more formally, the 3rd U. N. Conference on the Exploration and Peaceful Uses of Outer Space (COPOUS) in 1999. This meeting created the International Committee on GNSS (ICG), a voluntary body established to promote cooperation on matters of mutual interest related to civil satellite-based positioning, navigation, timing and value-added services. This group considers issues of compatibility and interoperability between the various systems (Fig. 6.3).

The GNSS providers (the United States, the EU, Russia, China, India and Japan), along with other interested member states of the United Nations and international organizations are members, and they have agreed that all GNS providers will openly publish documentation that describes signals, spectra and performance data. The publication of these 'interface control documents' are a key aspect of this process, as this is where each service provider documents the frequencies and technical aspects of their system for the international community.

The focus is on compatibility and interoperability, the exchange of detailed information on systems, and the exchange of views regarding ICG work plans and activities. The providers have developed a working definition of compatibility and interoperability, which include respect for spectrum separation between signals and addressing signal, geodetic reference and time standard considerations. The ITU provides the framework for discussions on radio frequency compatibility.

Currently, the present situation is defined by a number of bilateral arrangements between the various GNSS states, and there is not an overall or comprehensive agreement or structure. There is discussion of the need for an international convention on GNSS, which would reflect State sovereignty and authority and that would be subjected to international public law. This could address relevant issues relating to the future of GNSS services such as the rights and obligations of operators, liability issues, settlement of disputes, and the joint provision of new services. A reasonable approach, to be sure, but the reality is that the geo-political will is not there, and this is not likely to change in the near term.

Jamming of GNSS signals is a growing concern. Jamming of GPS, Wi-Fi and other signals is illegal in the United States and is a federal offense. In 2014, the Federal Communications Commission fined a Chinese electronics vendor, CTS Technology, a record US\$34.9 million and ordered it to stop selling signal jammers that interfere with authorized wireless communications, including GPS. The



FCC also ordered CTS to provide information about those who purchased these systems (Fig. 6.4).

Illegal small, local-area GPS jammers can be purchased on the Internet for US\$50, and fit into a car cigarette lighter. They jam all GPS signals near the car, and can be used for avoiding automatic electronic tolls and to stop employer or police GPS tracking. In 2013, a New Jersey engineering company employee purchased an illegal GPS jammer to keep his employer from tracking his GPS-equipped company vehicle. Unfortunately, he frequently drove past Newark International airport and disrupted the airport's and airline's GPS units on a daily basis. He was arrested and fined \$31,875 (and fired). (http://www.cnet.com/news/truck-driver-has-gps-jammer-accidentally-jams-newark-airport/.) There is now a system available to police that can locate these devices on the highway, as they are sometimes used to avoid electronic tolls. The FCC operates a toll-free number, 1-855-555NOJAM, or 1-855-556-6526, to report illegal jamming.

There have also been several reports of seemingly intentional disruptions of GPS timing signals at the London Stock Exchange from an unknown source. Finally, there are also multiple unverified reports of Russian GPS jammers being shipped illicitly to Iraq during the Iraq war, for use in jamming U. S. GPS-guided missiles, with very limited success.

Spoofing of GPS signals is another potential problem. This is where an electronic device is used to mimic the exact signal of a given GNSS satellite, which then broadcasts erroneous information. One technique, referred to as a 'carry-off' attack, is where the broadcast power is slowly increased, thus gaining precedence over the actual satellite's signal, and sending incorrect information to all receivers in that area.

Perhaps the largest concern of all would be some type of massive solar flare that released a powerful radiation surge, or even worse, a so-called coronal mass ejection (CME) from the Sun. If such a CME were of sufficient power and directionality, the billions of tons of ions traveling at millions of kilometers an hour could knock out or disable GNSS and other types of satellites that orbit above the protective Van Allen Radiation Belts. These events that can trigger a natural electromagnetic pulse (EMP) could have a major impact on currently deployed GNSS and communications spacecraft infrastructure that are now key to modern life on Earth. Even the discharge of a nuclear weapon in space could create an EMP that could disable key space systems. In short, GNSS satellites are potentially vulnerable to attack by jamming from the ground or EMP events from either cosmic hazards or even a nuclear attack.

GNSS Ethical Issues—Personal Tracking, LBS, and More

There are significant legal and ethical issues relating to these powerful new capabilities that relate to such issues as tracking of individuals without their knowledge, warrantless tracking of individuals by governments and police, storing and selling data on individual persons movements, stalking, etc. These are very new issues, and there are very few legal precedents.

Technologies develop much faster than the legal structure, and the decreasing size of GPS devices could lead to 24/7 tracking of individuals without their knowledge. GPS systems can be used to track employees, family members, or those suspected of crimes, and GPS 'leg bracelets' are routinely used to monitor hundreds of thousands of parolees and sex offenders. The tracking of employees can reasonably address efficiency and compliance with traffic laws and overtime rules for truck and bus drivers, but could also be abused. Rental car companies can now monitor the location and use of the vehicles to monitor for speeding, for example, in case of an accident and insurance claim.

Who owns this data? Who has access to it? Who is liable if it is wrong or wrongly used? In the United States, there are no federal laws regulating the use of GPS to monitor employees, but the states of California, Connecticut, Delaware, and Texas have such laws, which generally require employee consent. Delaware outlaws the use of GPS tracking of vehicles except by law enforcement and parents of minors. Texas allows private investigators to use GPS tracking devices, with the consent of the owner of the vehicle. U. S. courts have held that there is no expectation of privacy in relation to property owned by the employer, including cars, email and smart phones. In 2012 the U. S. Supreme Court decided that, without a proper warrant, police could not place GPS trackers on vehicles, as this was a warrantless search and thus was unconstitutional, but the question may be raised again.

Chapter 7 Conclusions and Future Directions

The following is a completely fictitious and fanciful tale that might explain, in part, exactly how we got where we are in the development of GNSS around the world today. This tale should be taken with a considerable grain of salt (i.e., caution) because it has been sewn together from some often suspect sources, from Wikileaks, and numerous unnamed sources who cannot speak publicly. In short, parts of this "fanciful narrative" may or may not be true.

Once, long ago, the U. S. military needed an improvement to the Transit satellite navigation system, and U. S. researchers developed an extraordinarily capable idea that would also be *very* expensive, costing tens of billions of dollars. In order to sell it to the U. S. Congress, the Pentagon claimed that it would also have amazing civilian and commercial uses, and that they would provide a civilian signal for this, and that there would follow new commercial markets and applications. They succeeded in getting the funding and building the system. No one was more surprised than the Pentagon when what they said actually happened, and the GPS system became a vital, global utility with thousands of unforeseen uses. This was made possible when President Ronald Reagan opened up the GPS civilian signal to the world after the shooting down of KAL 007.

The generals were also shocked when the early civilian component, which they had to include for purely political purposes, worked almost as well as the military receivers, so they created a "selective availability" system to reduce the civilian precision to make it nearly useless, but they did not turn it on. Then one day, they finally turned it on without telling anyone, and then only turned it off when the United States invaded Grenada and then Panama, and for the first Gulf war. This was because there were not enough military receivers yet available, and individual soldiers were buying every inexpensive GPS units on the market and having their families mail them to them in the field. Russia somehow found a way to develop their own exact copy of the GPS design, and claimed they thought of it first.

The United States was not overly concerned because the Glonass system was less capable, encrypted and only available to the Russian military. Both were, at their hearts, Cold War military systems, but the many uses of GPS began to quickly overtake the military market, and GPS became an amazingly useful scientific, commercial and business infrastructure. Europe felt left out, even though TomTom and other GPS developers were making millions by selling GPS units using the free GPS signal and without paying any license fees. So Europe decided to create its own system as a public-private partnership, with European industry paying the majority of the cost. The European business community, being no fools, quickly declined, as they saw no way to compete with a working GPS system that was provided for free and that met most users' needs.

European space and political leaders continued to lead the charge against the 'bad military' GPS (which by now it was not) and for creating a 'good civilian' Galileo system even though, as members of NATO, they had access to the P-code military system. The United States fought hard at the highest diplomatic levels against the development of Galileo, seeking to keep their advantage as the sole global military and commercial system. Europe also managed to rename the now generic use of the term GPS to GNSS, to differentiate this from the U. S. system.

Europe asked China, Israel and others to join in Galileo, partly for political cover but largely to get the millions needed to start development, and also to get the votes needed in the ITU to be given frequency allocations for the system, which the United States wanted to block. The United States fought hard against this. Europe decided that they would put their code frequency right on top of the U. S. frequency, and the United States was furious, as this would stop them from jamming Galileo in time of crisis if it was used against the United States. Europe said this was a stabilizing and good thing, but eventually, in the face of intense political pressure from the United States, relented and moved it. The United States fought hard against Galileo, and warned Europe that China was seeking advanced technologies for its own system. Europe disregarded this and saw China as too far behind to be a threat. China tried to buy atomic clocks in France and was denied, but purchased twenty in Switzerland and also bought, or otherwise acquired, much other advanced technology from European industry while a Galileo partner.

Europe won their Galileo frequency allocation in the ITU, and quickly dropped China and the others as partners, keeping the $\notin 2$ million already paid by China (which they never gave back). China was furious, and took all the technology it had bought (and otherwise acquired as fast as it could), and decided to create its own global Beidou system and to deploy it before Galileo, thus gaining frequency rights as the first to put the system in place. The United States and Europe fought hard against China's frequency access. China announced that it would put its frequency right on top of Galileo (just as Europe had tried to do to the United States), thus preventing Europe from jamming Beidou in time of crisis, and Europe was furious. China said this was a stabilizing and good thing, but eventually, in the face of much political pressure, relented and moved it slightly, but not enough to prevent mutual jamming. Europe felt that China had taken much of its technology improperly and had not played fair. China felt used by Europe, and wanted its €2 million back. Meanwhile, GPS had become such a global utility that the U. S. Coast Guard funded and fielded a Differential GPS network around the entire coast of the United States to defeat selective availability, and to ensure that ships entering U. S. harbors could navigate more safely with GPS. So one branch of the U. S. military (the Air Force) was keeping SA on, while another branch (USCG) was funding and fielding a U. S. government system to defeat it.

The Soviet Union collapsed, and Glonass dropped down to a few satellites and was no longer functioning. Thousands of other DGPS systems were in place around the world, and, finally, President Bill Clinton turned off SA for good, as people had developed a reliable and unjammable way to defeat it with DGPS. President Putin assumed power in Russia and made the rebuilding of Glonass a top priority, and the system was repopulated and enhanced. Putin also opened the signals to international and civil use.

Once China announced its own system, India felt the need to also have its own, and so announced the development of the Indian Regional Navigation Satellite System. Pakistan, India's enemy and China's ally, then felt the need to approach China, seeking its own Beidou satellite, and access to military receivers so that it can announce that it, too, have a satellite navigation system like India was developing, but Pakistan was denied this by China after long negotiations.

Pakistan did get a Beidou ground station located in Pakistan as a consolation prize, however, and could then say that it was a part of the system and on a par with India. China did not like India creating its own system, but could not block it. Since the Indian system was only regional, the United States, Europe, and Russia did not try to block it.

Brazil, which managed one of the most effective and useful space programs in the world, was perfectly happy using GPS, and wisely decided not to develop its own system, thus avoiding the development of the inevitable, competing Argentina and Chile regional systems. Vladimir Putin, having rebuilt Glonass, mandated the use of Russian receivers by commercial aircraft and other users, in order to develop and protect Russia's emerging commercial market, and Europe, unable to define a viable, long-term funding model, also considered creating protectionist barriers and requiring Galileo receivers in European aircraft and cell phones. European airlines and other industries, quite happy with the free GPS system they had used for decades, quietly fought hard against this, but it is almost certain that this will happen once the Galileo system is operational. Europe gave their industry a sneak peek at the inner workings of the Galileo architecture and signals, in order to give them an advantage in building and getting Galileo receivers to market, and the United States quietly fought against this, while U. S. and other scientists and researchers in the industry quickly decoded the first Galileo satellite transmissions (even though encrypted), and rapidly moved to market receivers that can use GPS, Glonass and Galileo signals even before Galileo was operational. Europe felt that this was unfair.

The United States now sought to rename the now generic use of the term GNSS to PNT, thus again regaining 'ownership' of the name of the technology back from Europe. Japan, politely, designed and launched their unique QZSS augmentation

system and nobody cared, as it was no military or economic threat. Australia, sitting in a geographical 'sweet spot,' where it will have free access to all of these systems being developed, sat back, smiled, and paid not a cent. Eventually, the United Nations created a forum whereby the various players were constrained to interact responsibly, and share detailed information on their systems to ensure interoperability and compatibility. International discussions ensued with all the expected complex, tense and diplomatically convoluted issues that continue to unfold. The dance continues today.

Having read this brief 'fanciful and perhaps at least partially true' history of GPS/GNSS/PNT, we must ask ourselves what the future is for these systems and their applications. We are quickly approaching a time when there will be four or five operational global GNSS systems, with upwards of 100–120 satellites, and between 20 and 40 satellites in view at any time from anywhere around the world. We only require four for accurate positioning.

What will this mean to end users? This will certainly provide better access and precision in areas such as urban canyons and under forest canopies. There will be improved ability at the poles as well, where there are virtually no users. We will have more options for software to provide faster and more reliable position fixes and initialization when first turning your receiver on. Accuracy will be enhanced, and the addition of signals from both the L1 and L2 frequencies will provide high precision for almost any imaginable application or user requirement, eventually including global, real-time millimeter precision. Dual frequency systems will limit the problems currently caused by the ionosphere. We will soon have global centimeter real-time positioning. If one system actually goes down, such redundancy will ensure continuous operation of vital systems around the world. But differences between use of CDMA and FDMA need to be resolved, as well as differences in geodetic references and time standards between the various systems, but these are all manageable.

From an optimal, end-user perspective, these individual systems need to work *together* in true interoperability, rather than simply exist as separate, even redundant, overlapping and competing entities. We need a global GNSS system of systems, rather than individual national capabilities. But there are also major issues regarding frequency overlap, jamming, and spoofing, and possible failure due to an extreme solar storm, and these concerns may well grow over time. There are also major legal and ethical issues that must be addressed. These issues will drive the possible business, commercial and scientific applications that will be possible in the future, such as Precision Agriculture, UAV piloting, and civil engineering, to name just a few.

True centimetric precision anywhere and anytime, and even indoor positioning will become widely available and costs will continue to decline, except in areas that engage in national protectionist barriers. GNSS will become even more of an invisible utility, used behind the scenes for a growing range of practical applications and markets around the world. But we cannot forget that these systems exist as a part of, and cannot be separated from, the global geopolitical context of powerful nation-states and their national security, economic competitiveness, technological development, and national pride. These systems are, even when provided freely, instruments of national will, and are not commercial or public benefit technologies.

Just as GPS replaced Transit with a vastly superior technology, there are new approaches to the determination of positioning and timing data that extend beyond the current generation of PNT technologies. Hybrid and Autonomous Positioning Systems, or HAPS, is an advanced concept where once a navigation and timing system is initialized, it can operate independently (including inside buildings, underground or underwater) for extended periods without requiring external updating. (Note: This is also a term of potential confusion, since the ITU has also come up with the term High Altitude Platform System—HAPS—to refer to drone systems deployed at high altitude for communications, observation or other purposes.)

The ultimate goal is to have a very small (single integrated chip) GPS system that includes its own atomic clock and a high quality Inertial Navigation System that does not drift like current generation INS systems do. Such a system, at least in a cost-effective and portable version, is not available at this time, but new developments in miniaturized, chip-scale atomic clocks, and miniaturized inertial measurement systems could be integrated with an advanced GPS system in the future. Remember what the first military GPS unit looked like, and how far we have come since then. Advanced concepts such as real-time data comparison with the real world could make available indoor positioning that would be very useful for a variety of applications such as fire-fighting, disaster response, and public safety. Advanced hybrid GNSS systems are also under development.

GNSS has become a mass commodity, and there is no disruptive advantage for new, redundant systems that provide the same basic capabilities and services. GPS is considered to be good enough for the vast majority of uses, yet new systems continue to be developed for dual use, national security, economic competitiveness, and national pride reasons. Multiple systems broadcasting open and interoperable signals do provide important benefits to all users, but we need to create functioning processes to resolve problems in frequency use and allocation as new technologies are developed. Limited frequency allocations and competing new technologies requiring scarce frequency allocations will continue to be a major problem. Important legal, liability and ethical issues are still to be addressed.

In the end, we must ask, how many of these do we need? We do gain by having more than one or two systems in terms or redundancy. But we do not gain in the same way, as end users, by going from three to four or five redundant systems. What is driving the desire to spend billions to create and operate at least five such competing systems? There are many answers to this, but the primary driver is the dual use nature of these technologies, national pride, and international economic competitiveness. PNT systems are, at their hearts, broadly defined national security systems, and the original justification and funding for the GPS system was for strictly military purposes. But the reality of the present is that commercial and public safety applications have far outpaced the military uses of these, and new applications are developed every month. PNT systems have become an invisible utility, enabling a wide range of vital purposes, and these will only increase in number as costs decrease and new markets emerges. We must find better ways to coordinate and cooperate in this PNT arena, to ensure that this amazing ability to master both geographical space and time continues to provide broad benefits to all peoples on Earth.

Chapter 8 Top Ten Things to Know About GNSS

This brief book covers a great deal of background and detail about GNSS networks and services. Some of the chapters provide what many might consider minutiae about the various coding and other systems available to obtain great precision for some applications like geodesy to track continental drift. This final chapter tries to boil down some of the most important points covered in this book that might be considered some of the key "takeaways" that are important to remember.

- 1. Space-based GNSS systems play an important and growing role in our lives and have become an invisible utility serving a growing number of purposes.
- 2. These technologies are relevant to all nations regardless of their level of economic or technological development.
- 3. A day without GNSS would be a bad day on the ground, and many vital military, transportation, financial and other services would be severely disrupted in such an eventuality. Backup planning with regard to possible loss of GNSS against cosmic hazards and manmade electromagnetic pulse (EMP) events is currently an area that emergency planners are seriously addressing.
- 4. The integration of many different types and sources of data, using geomatics, is the key to the future. In the next few decades GNSS data will be increasingly integrated with other types of information and services. This will serve to make them even more invisible but no less vital. In this world, sorting out market size will be even more difficult.
- 5. PNT (or GNSS) systems have quickly become an invisible utility that supports many practical benefits that people do not consider to be involving space, and these systems depend upon government-operated systems that are provided freely. People often forget what would be the consequences if vital governmental services that are often "free" were to disappear. Weather forecasting and violent storm warning, air traffic control, emergency and disaster recovery and relief, and GNSS services are just a few of those truly vital governmental services today.

- 6. There will be many competing (or at least complementary) systems in the near future, with much redundant cost and limited overall benefit. This is driven by the dual use nature, and particularly the military use of these technologies and their tremendous commercial potential. This redundancy, however, could have great value if one or more of these GNSS networks were damaged or severely impaired by an intentional act of sabotage, a severe solar event such as coronal mass ejection, or an EMP.
- 7. There is no real benefit or advantage to the end user for so many overlapping systems that provide the same basic capabilities and services, except for the redundancy that provides protection against a loss of service.
- 8. It is uncertain if all GNSS providers will continue to offer free and in the clear services, or devolve into competing, protected regional markets mandating the use of the local technologies within protected markets.
- 9. In the future we will find even more uses of PNT services, but there are important legal and ethical issues to be addressed.
- 10. Perhaps one day we will have an integrated, efficient and internationally coordinated PNT capability, but this is not in the immediate future.

Appendix A Key Terms and Acronyms

AK	Authentication key
A-GPS	Augmented GPS
ADS-B	The U. S. Automatic Dependent Surveillance and Broadcast
	system
APL	The Applied Physics Laboratory of Johns Hopkins University
ARGOS	Environmental satellite telemetry system
AS	Anti-spoofing
ATC	Ancillary Terrestrial Component
Biedou	Chinese satellite navigation system (Big Dipper)
BIH	Bureau international de l'Heure
BPS	Bits per second
C/A Code	The civilian GPS Course Acquisition Code
CD	Clock drift
CDGPS	Canada-wide Differential Global Positioning System
CDMA	Code Division Multiple Access
CEP	Circular Error Probability
CISPR	International Space Committee on Radio Interference
CL	Long Code
СМ	Moderate Length Code
CME	Coronal Mass Ejection
CNES	Centre National d'Etudes Spatiales, the French Space Agency
Compass	Chinese second generation satellite navigation system, also called Biedou II
COPUOS	The United Nations Conference on the Exploration and
	Peaceful Uses of Outer Space
CORS	Continuously Operating Reference Stations
COSPAS	Cosmitscheskaja Sistema Poiska Awarinitsch Sudow (Russian:
	space system for search of vessels in distress)
COSPAS-SarSAT	International satellite distress system
DAGGER	Defense Advanced GPS Receiver, second generation U. S. military hand-held GPS receiver

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DASS DGNSS DGPS DNSS DoD DOP Doppler Shift	The U. S. Distress Alerting Satellite System Differential Global Navigation Satellite System Differential Global Positioning System Defense Navigation Satellite System precursor to GPS U. S. Department of Defense Dilution of Precision The change in frequency when a device transmitting either
Dual Use	moves towards or away from you The use of a system, network, or satellite infrastructure to support both military (i.e. strategic defense) and civilian applications and services at the same time
EDM	
EEPROM	Electronic Distance Measuring
EEPKOM	Electrically Erasable Programmable Read Only Memory Exclusive Economic Zone
EGNOS	European Geo-Stationary Navigation Overlay System
Electro-L	Russian satellite
ELT	Cospas-Sarsat Aviation Emergency Locator Transmitter
EMP	Electro Magnetic Pulse
EPIRB	Cospas-Sarsat Marine Emergency Position Indicating Radio
LI IKD	Beacon
ESA	European Space Agency
EU	European Union
EUMETSAT	European Meteorological Satellite Organization
FAA	Federal Aviation Administration
FCC	Federal Communication Commission
FDMA	Frequency Division Multiple Access
FTP	File Transfer Protocol
GAGAN	GPS Aided GEO Augmented Navigation (Indian WAAS)
GaIn	Galileo Industries
GDOP	Geometric Dilution of Precision
GEO	Geostationary Satellite Orbit
GEOSAR	Geostationary Satellite Search and Rescue
GIOVE	Galileo In-Orbit Validation element Galileo test satellite
GLONASS	Russian Global Navigation Satellite System ("GLObalnaya
ULUNASS	NAvigatsionnaya Sputnikovaya Sistema")
GNSS	Global Navigation Satellite System
GPS	U. S. NAVSTAR Global Positioning System
GSA	European GNSS Agency
GUS	Ground Uplink Station
HAPS	High Altitude Platform System (ITU Term)
HAPS	Hybrid and Autonomous Positioning Systems
HDOP	Horizontal Dilution of Precision
HEO	Highly Elliptical Orbit
ICAO	International Civil Aviation Organization
ICAU	international Civil Aviation Organization

ICD	Interface Control Documents of the International Committee
	on GNSS
ICG	International Committee on GNSS
IJPS	Initial Joint Polar System of METSAT and NOAA
IMO	International Maritime Organization
INRSS	Indian Navigation Regional Satellite System
INS	Inertial Navigation System
INSAT	Indian GEO satellite
ISRO	Indian Space Research Organization
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunications Union
KGPS	Kinematic GPS
L1	The 1575.42 MHz GPS carrier frequency including C/A and
	P Code
L2	The 1227.60 MHz secondary GPS carrier frequency (P Code
	only)
L2C	The L2 civilian code transmitted at the L2 frequency
	(1227.6 MHz)
L5	3rd civil GPS frequency that tracks at low signal-to-noise
	ratios (1176.45 MHz)
LAAS	Local Area Augmentation System
LBS	Location Based Services
LEO	Low Earth Orbit
LEOSAR	Low Earth Orbit Search and Rescue
LORAN	LOng RAnge Navigation ground based radio navigation system
LUT	Cospas-Sarsat Local User Terminal
MCC	Cospas-Sarsat Mission Control Center
METOP	EUMETSAT satellites
MEO	Medium Earth Orbit
MEOSAR	Medium Earth Orbit Search and Rescue
MHz	Megahertz
MSGPS	USCG Maritime Differential GPS System
MTSAT	Japanese Multi-functional Transport Satellite Augmentation
	System
Nadejda	Soviet polar orbiting environmental satellites
NASA	National Aeronautics and Space Administration
NAVSTAR	NAVigation Satellite Timing and Ranging (GPS)
NDGPS	U. S. Nationwide Differential GPS System
NGS	The U.S. National Geodetic Survey
NOAA	National Oceanographic and Atmospheric Administration,
	U. S. Department of Commerce
NUDET	Nuclear detonation sensors on GPS satellites
P-Code	The GPS military Precise code
P(Y)	The Precise Positioning Service provided on L1 and L2
Parus	Early Soviet military satellite navigation system

PDOP	Position Dilution of Precision
PLB	
PMT	Cospas-Sarsat Personal Locator Beacon Argos Il Platform Messaging Transceiver
	6 6
PNT	Precision Navigation and Timing
POES	Polar Orbiting Environmental Satellites of NOAA
PPS	Precise Positioning Service
PPT	Argos Platform Transmitter Terminals
PRN	Pseudo Random Noise
PRN#	Pseudo Random Noise number
Project 621B	U. S. Air Force satellite navigation system in development before GPS
PRS	Public Regulated Service (Galileo)
Pseudolite	A false, ground-based GNSS satellite, used for local systems
QZSS	Japanese Quazi-Zenith Satellite Augmentation System
MSAS	Japanese regional space-based augmentation system
RCC	Cospas-Sarsat Rescue Coordination Center
RF	Radio Frequency
RIMS	European EGNOS Ranging and Integrity Monitoring Stations
RMS	Root mean square
RTK	Real time kinematic GPS
SA	Selective Availability, the intentional degradation of the
	civilian GPS signal
SARSAT	Search and rescue Satellite Aided Tracking
SBAS	Satellite Based Augmentation System
SDCM	Russian regional space-based augmentation system
SGS-90	Soviet Geodetic System 1990
SNAS	Satellite Navigation Augmentation System (China)
SPS	Standard Positioning System, the GPS civilian C/A code
	signal
Sputnik	The first Soviet satellite
SSAS	Argos-based Ship Security Alert System (SSAS)
SV	Space vehicle
TAI	Temps Atomique International or International Atomic Time,
	the basis of UTC Coordinated Universal Time
TDOP	Time Dilution of Precision
TEC	Ionospheric Total Electron Count
Timation	U. S. Navy satellite system developed before GPS
TOA	Time of Almanac
TOE	Time of Ephemeris
TTFF	Time to first fix
Transit	First U. S. satellite positioning system
Tsikada	The first Soviet satellite positioning system
USCG	United States Coast Guard
USGS	United States Geological Survey
UTC	Coordinated universal time

Appendix A: Key Terms and Acronyms

UTM	Universal Transverse Mercator map projection
VDOP	Vertical dilution of precision
VMS	Vehicle monitoring systems
VRA	Variable rate application systems for precision agriculture
VTS	Vehicle tracking systems
WAAS	Wide area augmentation system for GPS in the U.S.
WADGPS	Wide area DGPS
WAGE	U. S. Military wide area GPS enhancement system
WGS	World geodetic system
WGS84	World geodetic system version 1984
WCRP	World climate research program

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Appendix C Selected Websites

GPS World Magazine www.gpsworld.com

Inside GNSS Website www.insidegnss.com

Current U. S. GPS System Performance Standard and GPS Modernization http://www.gps.gov/technical/ps/2008-SPS-performance-standard.pdf

The Future of GNSS https://courseware.e-education.psu.edu/downloads/geog862/Lesson4_FutureGNSS.pdf

European GNSS Asia Market Report http://www.gnss.asia

EGNOS http://egnos-portal.gsa.europa.eu

U. S. Government GPS site http://www.gps.gov

Glonass http://new.glonass-iac.ru/en/

Chinese Beidou website http://En.beidou.gov.cn

Galileo Website http://www.gsa.europa.eu/galileo/why-galileo

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Indian IRNSS website www.isro.org/satellites/irnss.aspx

Inside GNSS http://www.insidegnss.comm

UNAVCO Page http://www.unavco.orgg

UNAVCO GPS/GNSS Data Page http://www.unavco.org/data/gps-gnss/gps-gnss.htmll

UN Office of Outer Space Affairs (OOSA) http://www.oosa.unvienna.orgg

UNOOSA GNSS Educational curriculum http://www.oosa.unvienna.org/pdf/icg/2013/Ed_GNSS_eBook.pdf

U. S. Coast Guard Navigation Center www.navcen.uscg.gov

WAAS The Wide Area Augmentation System http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/ navservices/gnss/waas/