replenishing the system, the size of the orbital groups was decreased. In 2001, the orbital constellation consisted of six functioning satellites. They were part of a Glonass/GPS joint use mode and methods were developed to use it in various areas. At present, resources have been allocated to supply the system and develop satellites with 5- and 7-year service lives. It is proposed that the system will be restored to its full complement by 2010. Measures have been mandated to increase accuracy by using onboard clocks with instability of 1×10^{-13} and a ground-based hydrogen standard of 1×10^{-14}, and also devices for comparing timescales of onboard clocks with the ground-based standard whose error is 3–5 nanoseconds. The potential of this system is far from exhausted. Its potential is in the continuous updating of the system and the development of in-depth integrated systems for controlling the motion of moving objects. It is considered that the Glonass system must function as an independent system and also in conjunction with GPS and other navigational systems being developed.

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GLOBAL POSITIONING SYSTEM (GPS)

Introduction

The Global Positioning System, commonly referred to as GPS, is a worldwide, satellite-based positioning and timing system that allows suitably equipped radio receivers to locate themselves in four dimensions, latitude, longitude, altitude, and time, anywhere there is a reasonably clear view of the sky. The system is also known as NAVSTAR, a convenient nickname that is not an acronym. The GPS system was developed, deployed, and is currently operated by the U.S. Air Force. GPS enables precision weapon delivery for all branches of the U.S. Department of Defense, as well as allied nations. Additionally, GPS supports civilian positioning and was always intended to support civil operations. The complete satellite constellation and ground support equipment that make up GPS was declared "operational" in December 1994, although civil use of the developmental signals started in the early 1980s. Initially, the civil signal was deliberately perturbed to prevent hostile use; this greatly degraded the civilian signal accuracy. This perturbation was called selective availability (SA), but the widespread advent of differential GPS, which calibrated these errors in real time, rendered this totally ineffective. In 1996, the President ordered this perturbation stopped, pending justification from the Department of Defense. In 2000, the selective availability perturbations in the signal were completely removed.

The fundamental operation is as follows: the 24 GPS satellites (see Fig. 1) are uploaded from the ground with their current and predicted positions (called ephemeris or orbital parameters). Small corrections of their space-borne atomic clocks are also uploaded. This information is broadcast to the user as a data modulation on an L-band signal (1575 MHz for most civilian users) that doubles

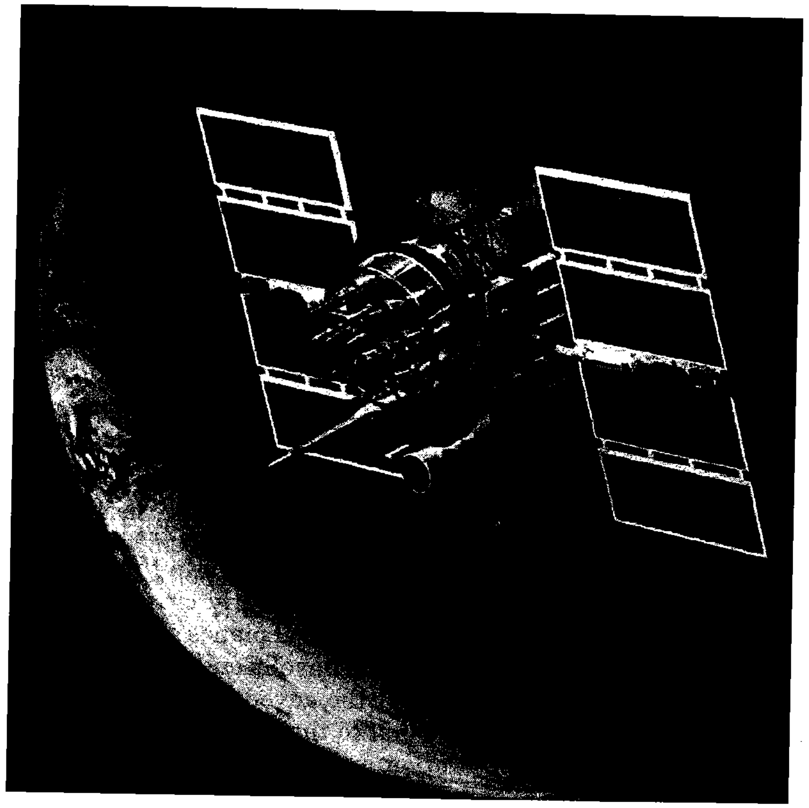


Figure 1. Early GPS satellite. A phase one GPS satellite built by Rockwell (now Boeing). This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

as a precise, one-way ranging signal. Ranging is achieved by synchronizing the start time of a pseudorandom sequence of bits transmitted from the GPS satellites at an accuracy of about one nanosecond (10^{-9} s). Three very important results are achieved by this implementation. First, this makes GPS ranging a one-way signal that allows an infinite number of users to receive the signal and compute their position without saturating the GPS system. Additionally, this makes the GPS receiver passive, so that it does not radiate radio-frequency (RF) energy. Last, by receiving four or more satellite signals, users can synchronize their local clocks to GPS time, obviating the need for a very high quality and very expensive atomic clock in the receivers.

An important feature of the system is that all satellites broadcast on the same nominal frequency but use different modulation codes that are nearly orthogonal to each other. This technique is referred to as code division multiple access (CDMA). These codes are called pseudorandom noise or PRN codes. The user separates the signal from each satellite by correlating the incoming signal with an internally generated replica of the code for each of the satellites in view. The actual range measurement is the corrected difference between the phase of these codes and the local user's clock (called *pseudorange* because the true range is offset due to the local clock bias). Algebraically, four (or more) measurements allow the user to solve simultaneously for the four dimensions of location x, y, z, and t. More than four measurements allow improved accuracy and can also be used to monitor the integrity of the computed solution. A more detailed description of the Concept of Operations can be found in a later section.

GPS system accuracy, it can be shown, is a function of both the ranging accuracy from the satellites and the geometry of the satellite constellation being received. Typically 6 to 11 satellites are in view for users anywhere in the world who have clear views of the sky. Errors will be discussed later; typical civilian GPS positioning accuracies for nominal satellite geometries are summarized in Table 1. A full capacity GPS receiver can measure position, *velocity*, and *attitude* using multiple antennae. Thus, thirteen quantities can be measured by GPS: time (t) and the three dimensional position (x, y, z) and velocity (u, v, w), as well as the three attitude rotations (ψ, $\oint$, θ) and the associated attitude rotational rates (p, q, r).

GPS is made up of three logically different systems that are commonly referred to as segments. The three fundamental GPS segments are the space segment, the ground control segment, and the user segment. The space segment (see Fig. 2) consists of approximately 24 satellites in six inclined orbital planes that have periods of 12 sidereal hours (11 hours, 56 minutes, and 4 seconds). Except for small perturbations, each satellite has a ground trace that is repeated twice per (sidereal) day. The corresponding altitude above the mean equatorial radius of the earth is 20,163 km. The orbits are nearly circular to keep the received power of the signal constant, and the orbital planes are nominally inclined 55° to the equator. All operational satellites have been launched from Kennedy Space Flight Center on Delta rockets, but the advent of the evolved expendable launch vehicle (EELV) will cause a switch to those vehicles. The space segment receives uploaded predictions of location and time corrections from the control segment and stores them for transmission to users. Three navigation signals are currently being broadcast: a civilian signal (called L1C) at 1575.42 MHz that has a modulation bit rate of 1.023 MHz; a military signal (called L1P/Y) also at 1575.42 MHz that has a modulation bit rate of 10.23 MHz; and a military signal (called L2P/Y) at 1227.6 MHz that has a modulation bit rate of 10.23 MHz. Details of the signal structure are given in Operational Concepts.

Table 1. **Nominal GPS Median Accuracies for Civilian Users**[a]

Dimension	Operation					
	Nominal	Local differential	Wide-area differential	Carrier differential	Survey	Time transfer
Horizontal	10 m	0.5 m	1.0 m	0.01 m	0.001 m	NA
Vertical	20 m	1.0 m	2.0 m	0.02 m	0.002 m	NA
Time	50 ns	NA	NA	NA	NA	3 ns

[a] This table displays the GPS accuracies for civilian users with four or more satellites in view and reasonable geometries as a function of type of receiver and aiding. Nominal accuracies are indicative of a stand-alone, single-frequency code receiver. Differential aiding improves the accuracy of the position but does not affect the time, and the improvement in position is a strong function of the distance from the differential station. Carrier phase techniques provide enormous gains in positioning accuracy but require additional time and computation to solve for the unknown carrier cycles between the differential station and the user.

The control segment consists of five or more monitor stations, four ground antenna upload stations, and the Operational Control Center (OCS—Located at Schreiver AFB outside Colorado Springs, Colorado). A backup control center is planned for Vandenberg AFB, California. Each monitor station measures the ranges to all satellites in view, smooths these measurements, and transmits these data to the OCS for further processing. The OCS predicts future satellite locations and satellite clock corrections. These data are then appropriately formatted and sent to the upload stations for relay to the satellites. The information is retained in satellite memory and sent to users as part of the data modulation scheme, at 50 bits per second. GPS is designed to retain its functionality, albeit at a degraded level, in the unlikely event that the ground stations cannot upload the data to the satellites. Modernization plans for the GPS constellation include satellites that can communicate directly with each other at higher data rates. This will provide greater capability in the event of loss of ground contact.

The user segment consists of the receivers, which lock on the signal, demodulate the data, calculate the corrected ranges, and transform this into position, velocity, and time. Differential transmitting stations (see Fig. 3) are considered part of the user segment, even though some of these may be other satellites (e.g., Wide Area Augmentation System—WAAS, Fig. 4) or transmission towers operated by the government (e.g., National Differential GPS—NDGPS, Fig. 5).

A Brief History of GPS

For 6000 years, humans have been developing ways to navigate to remote destinations. Driven mostly by the desire to transport goods by ship, early navigators remained within sight of land using a technique known as "piloting" that relied on navigators' recognition of coastal features. The magnetic compass

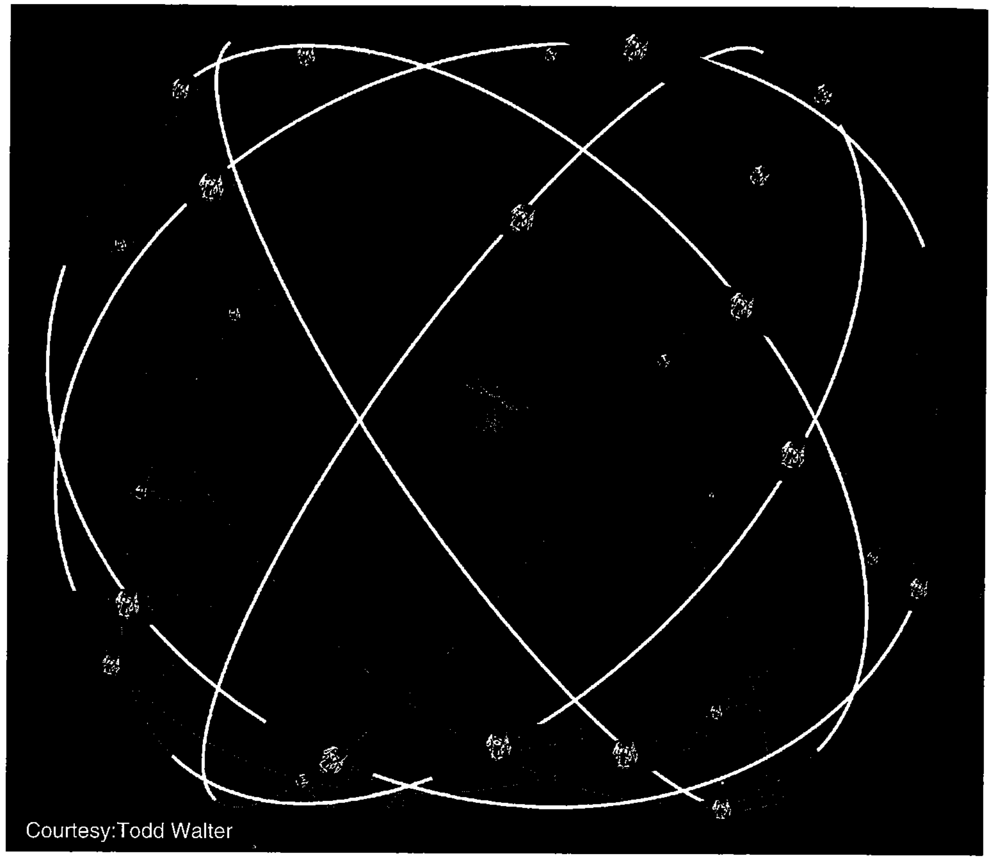


Figure 2. The GPS constellation consists of 24 satellites in six orbital planes. The orbital planes are nominally inclined at 55° and contain four satellites each. The satellites are not placed symmetrically around the orbital plane, but instead are placed in such a way that any single satellite failure has minimal impact on GPS. The orbital altitudes are 20,163 km above the equator. Some of the orbital planes may have extra satellites as on-orbit spares. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

appeared in China around the 1100 C.E. and in Europe approximately a century later. When forced to traverse a stretch of water outside the view of land or in inclement weather, navigators kept track of their position by "dead reckoning." Navigators would record their heading and distance traveled by hourglass timing the passage of wooden logs thrown off the bow. Needless to say, the technique was notoriously inaccurate. The development of a sextant by 1731 (early versions existed in the thirteenth century) made determining latitude fairly routine. Early efforts to navigate precisely at sea led to so many deaths that in 1714 a King's ransom was offered to anyone who could solve the problem of computing longitude (1). During the eighteenth and nineteenth centuries, the navies of the world refined optical instruments and timekeeping. This allowed reliance on the stars and planets to locate their ships precisely. These celestial navigation techniques fundamentally required angular measurements between

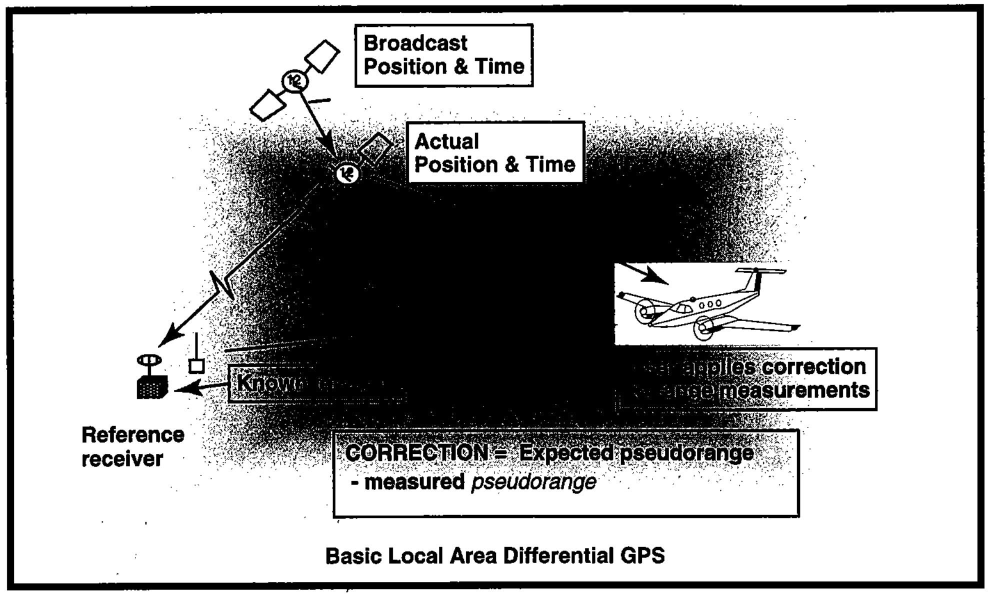


Figure 3. Block diagram of Basic Differential GPS. Differential corrections are broadcast to the user from a receiver in a known location that computes the correction from the difference between its known location and the GPS-measured position; hence the term "differential" corrections. The error at the reference receiver and the user are correlated across distance and time so that great improvement can be achieved across smart distances and small time lags (typically 5–10 km and several minutes of latency). Note that the primary reason for using differential had been to reduce the effects of selective availability; when SA is off, much better accuracies and integrities are achieved. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

the local horizon and the Sun, stars, or planets to find lines of position. Due to the motion of Earth, each angular measurement had to be carefully timed to attain the required accuracy. Earth's "rim speed" at the equator is about 1500 km/h, or 24 km min; thus a 1-second error translates to about one-half mile. (On the other hand, because GPS uses the time of flight of a radio signal, a 1-second error for GPS translates into 300,000 km error in position.)

At the turn of the twentieth century, Marconi successfully transmitted radio waves across the Atlantic. By the 1930s, aircraft navigation was becoming a concern, and radio-navigation techniques were in their infancy. Early aircraft navigation aids consisted of direction-finding equipment, which gave a bearing to the transmitting station. Radio techniques such as radio beacons and LORAN were invented to overcome the limitations of celestial navigation and were largely deployed by the end of World War II. These techniques provided all-weather, 24-hour navigation service, but only within range of the signals.

GPS Predecessor: TRANSIT. In October 1957, the Soviet Union launched "Sputnik," the world's first space satellite. This triggered a flurry of activity within the United States to discover the exact details, especially the nature of its orbit. Two researchers, Dr. Guier and Dr. Wieffenbach, at the Johns Hopkins Applied Physics Laboratory (APL) had carefully studied Sputnik's radio signal

Figure 4. The Wide Area Augmentation System (WAAS) architecture. The basic functionality of the WAAS system is to use a widely spaced set of reference stations to produce a set of vector corrections for all users within the coverage space. Data is aggregated at each station and processed into a global set of corrections at redundant WAAS Master Stations (WMS) and in turn uplinked to satellites in GEO orbits. These satellites broadcast a message that allows users in the coverage area to compute their own corrections based on the WAAS data and rough knowledge of their own positions. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

and noted certain regular features. The most interesting of these features was the Doppler shift as the satellite passed overhead. This was caused by the change in the length of the line of sight and was enhanced by the satellite's high speed and low altitude. These scientists developed a computer program to determine Sputnik's orbit (2). Dr. McClure of APL, a colleague, realized that the problem could be turned on its head; the process could be reversed. By measuring the Doppler shift to a satellite of known orbit, listeners could calculate their own positions (3). This solved an important problem for the U.S. Navy that yielded precise all-weather positions for submarines and other ships. After speedy approval, a program was initiated under APL's management. The first two developmental TRANSIT satellites were launched by 1960, and the system became operational by 1964 (4).

TRANSIT eventually deployed an operational constellation that included about five polar orbiting satellites. They produced fixes every 35 to 100 minutes and provided horizontal accuracies of 100 meters or better for a stationary user. A moving receiver could compensate for velocity with some degradation in accuracy. TRANSIT was not generally used by aircraft due to the incompatibility of TRANSIT with the rapid platform motion of an aircraft. Additionally, aircraft require the third dimension (altitude) that the TRANSIT system did not provide. TRANSIT was, however, an important predecessor to GPS and pioneered a number of key technologies and concepts. TRANSIT led to a great refinement of Earth's gravity field model, successfully tested dual-frequency correction techniques for ionospheric induced delays, and was crucial in developing stable and reliable frequency sources. TRANSIT provided only periodic updates and the degradation for a moving user made it unsuitable for aircraft. By the late 1960s, better systems were being explored by the Navy.

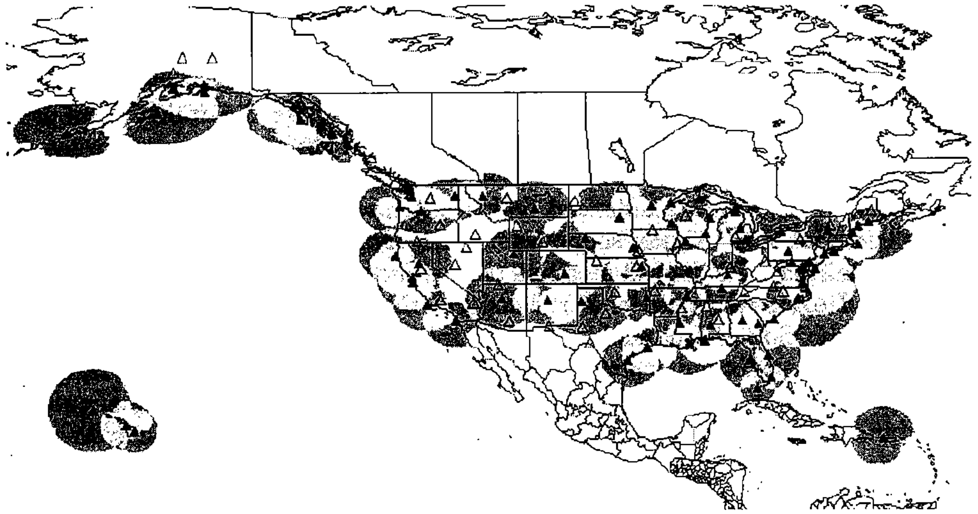


Figure 5. U.S. National Differential GPS System. This map shows the coverage of the NDGPS system as of 2001. Existing stations broadcast corrections in the 300 kHz band and generally have a range of 100–250 km. The current system covers the entire coastline and navigable rivers. Future upgrades are being deployed that will remove the gaps in coverage of the entire continental United States. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

Additional GPS Predecessors: Timation and 621B. Timation was a program under the Naval Research Laboratory (NRL) whose goal was orbiting very accurate clocks. These clocks were to be used to transfer precise time among various laboratories around Earth. Under certain circumstances, users could also determine their positions by using the Timation signal. The approach was somewhat different from TRANSIT in that the radio signal allowed direct ranging by using a technique known as side tone ranging. Two satellites had been launched prior to the approval of GPS phase one in 1973. After that date, the Timation research effort was folded into the GPS development program. The NRL expertise played a key role in developing the atomic clocks used on GPS (5).

The third predecessor to GPS was a U.S. Air Force program called 621B. This effort was directed by an office in the Advanced Plans group at the Air Force's Space and Missile Systems Organization (SAMSO) in El Segundo, California. This concept was strongly supported and advocated by Dr. Getting of the Aerospace Corporation. This program evolved directly into GPS, although not before significant modifications were made to the original U.S. Air Force-only concept. By 1972, 621B had already demonstrated operation of a new type of satellite ranging signal based on pseudorandom noise (PRN). Successful aircraft tests had demonstrated the PRN technique using ground-based "simulated" satellites located on the floor of the New Mexican desert.

The PRN modulation used for ranging was essentially a repeated digital sequence of fairly random bits (ones or zeros) that possessed certain useful properties. The sequence could be generated by using a shift register or for shorter sequences, could be stored in very little memory. Given the limited capabilities of computers then, this was a crucial feature. A navigation user could detect the "phase" or start of the signal sequence and use this for determining the range to the satellite. The PRN signal also has powerful noise rejection features and can be detected even when its power density is less than one-hundredth that of ambient radio noise. Furthermore, all satellites could broadcast on the same nominal frequency because properly selected PRN codes were nearly orthogonal.

When "tuned in" to a particular PRN sequence, all other PRN sequences appear to the user as simple noise. The PRN sequence can be tracked even in the presence of large amounts of noise, so other signals on the same frequency do not generally jam the signal of interest. The ability to reject noise also implied a powerful ability to reject most forms of jamming or unintentional interference. In addition, a communication channel could be included by inverting groups of the repeated sequences at a slow rate (50 bits per second is used in GPS). This communications channel allowed the user to receive the ephemeris, clock, and health information directly as part of the single navigation signal. The original Air Force concept visualized several constellations of satellites in highly elliptical orbits with 24-hour periods. This constellation design allowed deploying the satellites gradually (for example, to cover North America first) but complicated signal tracking due to the very high line-of-sight accelerations. Initially, the concept relied on continuous signal generation on the ground with continuous monitoring and compensation for ionospheric delays.

Program 621B was the immediate predecessor of the GPS effort, but the program came perilously close to cancellation several times a 10 year perspective on the history of GPS is in Ref. 6). In the early 1970s, Dr. David Packard, the Deputy Secretary of Defense, instituted important changes at the Department of Defense. One of these changes was to encourage joint programs that had multiple service participation. It turned out that GPS was the first "Joint Service" program. The first program director was Col. (Dr.) Bradford Parkinson, one of the authors of this article (one of the other authors is Dr. Jim Spilker who played a lead role in the design of the GPS signal structure). Dr. Parkinson was assigned to 621B in November 1972 and was directed to gain approval for the concept validation phase of the Defense Navigation Satellite System (DNSS), as the new DOD satellite navigation system was originally known. After many briefings of senior personnel in the Pentagon, a Defense Systems Acquisition Review Council (DSARC) meeting was held in August 1973, at which Dr. Parkinson presented a brief on the Air Force 621B program (7) approval was denied.

Meanwhile, Dr. Parkinson had presented the concept to the Director of Defense Research and Engineering, Dr. Malcomb Currie, who quickly appreciated the value of a three-dimensional, continuous, 10-meter positioning system. After the failure to gain approval, Dr. Currie invited Dr. Parkinson into his office and asked him to rethink the system and to ensure that it truly was a Joint Program, one that incorporated the best technology and concepts across DOD. He wanted a synthesis, a new all-encompassing concept. Dr. Parkinson assembled about 10 of his key program members in the halls of the Pentagon during Labor Day weekend 1973. The result was a new system concept that was later named GPS, or NAVSTAR. By mid-December 1973, the senior DOD officials had been briefed and the reconvened DSARC gave approval. By June of 1974, the satellites, ground control system, and user equipment was on contract.

The first GPS satellite was launched in February 1978 and led to successful validation of the concept. The subsequent operational satellites incorporated certain additional nonnavigation payloads, which enhanced their value, but also undoubtedly delayed full operation. At the same time, the U.S. Air Force was not comfortable with having to shoulder the whole financial burden for the program and attempted to cancel GPS at least three times. In each case, civilian leadership (including the editor of this *Encyclopedia*) overruled the suggestion. GPS was declared operational in December 1995, although both civilian and military users had been using the available developmental system for more than 10 years.

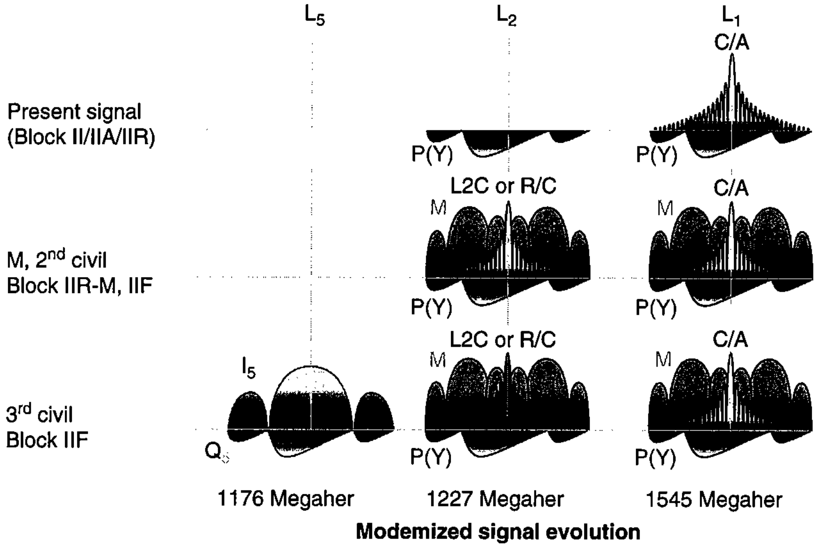
Due to the possibility that potential enemies might use GPS positioning against the United States or her allies, the civil signal was intentionally degraded through a process known as selective availability (SA). SA reduced accuracy for civilian users and remained part of GPS as a holdover from its original military history. SA was generally active, although ironically it was turned off during several national emergencies and international military campaigns due to the widespread military use of civilian receivers. It was slowly realized that the proliferation of differential corrections in the form of augmentations rendered these perturbations totally ineffective. As a result, a Presidential Decision Memorandum (PDM) was signed in 1996, which ordered the military to discontinue its use, pending justification from the DOD. In early 2000, SA was removed from the signals of all orbiting satellites.

During the first 25 years of GPS, several generations of satellite designs have been developed or are under development. These include I, II, IIA, IIR, IIRM, and IIF. In addition, there are plans for an upgraded version of GPS, known as GPS III, which is currently being defined. The Block IIRM and Block IIF satellites add additional civil GPS signals at other microwave band frequencies (see Fig. 6), which should materially improve the accuracy and robustness of the service (8).

GPS Concept of Operation

The design objectives of the GPS system were to provide a continuously available, worldwide, all-weather, three-dimensional precision navigation system for both military and civilian users on land, at sea, or in the air (or even in space). The GPS system had to operate, even on an accelerating platform such as a maneuvering aircraft or missile. Additionally, the system had to be passive, or one-way, so that it could service an unlimited number of users. As a military system, the signal is required to be both jam-resistant and antispoof.

Each of these requirements drives a certain set of constraints. To be worldwide and continuously available, only a satellite system can provide global



Courtesy:Aerospace Corporation

Figure 6. The GPS signal is undergoing modernization in preparation for GPS III. The current system is shown in the topmost frame with P/Y code on both the L1 and L2 frequencies, and the C/A (civil) code only on L1. The signal modernization calls for broadcasting a second copy of the C/A code on L2, and the military will get a new spread-spectrum code, called M-code, on both L1 and L2. The M-code is structured to broadcast most of its power into the nulls of the C/A code, maximizing spectral separation. A third civil frequency on L5 is set to be implemented on the late Block II-F satellites. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

coverage, especially over the oceans and polar regions. As a satellite system, frequencies less than 1 MHz skip off the ionosphere, and frequencies higher than 10 GHz are very heavily attenuated by atmospheric moisture. Satellite signal frequency was a compromise among accuracy (ionospheric delay), attenuation, and the power to be received by an omnidirectional user antenna. Thus, the selected signal was placed within the L band for best performance. Two additional constraints were established by the military: that the satellites could be totally serviced from the continental United States (CONUS) and that the constellation could be tested by using a small number of satellites to minimize project risk. These constraints led to satellites in MEO orbit, which costs significantly less in energy than a GEO orbit.

The quantitative requirements of the original GPS design were (1) to guide a bomb to within a 10 meter circle anywhere on the planet and (2) build an inexpensive ($<$\$10,000) device that could navigate.

Multilateration Positioning System. GPS functions as a multilateration, or rho-rho (ρ-ρ), system, that is, the range from at least three known locations is determined and the resulting intersection of the three spheres defines a single point that is the user location. In GPS, the system is complicated by the fact that the transmitters are moving and that the range cannot be measured directly. As a simplification, assume that the GPS satellites are stationary and that the user is upon a flat nonrotating Earth. All of the satellites are synchronized and transmit a signal at the exact same time.

The user will receive the signal from each satellite at a different time due to the time of flight of the signal from the satellite to the user across the various ranges to each satellite. If the user possessed a very accurate clock that was time synchronized with the satellites, then the product of the time of flight and the speed of light would be the true range to the satellites. However, because the user is unlikely to have an atomic clock (a requirement which would make the receivers far too expensive), the user is not synchronized to GPS time. Thus, the measured range is offset by a consistent bias and is thus referred to as pseudorange (ρ):

$$\rho_i = c \times t_i + b, \tag{1}$$

where c is the speed of light, t_i is the true arrival time, and b is the range equivalent bias in the user clock (time converted to meters). This measurement is taken simultaneously for each satellite. Even without knowing the exact time, the consistent solution for the ranges based on the user position and unique time bias can be computed. The general solution is nonlinear. The simplified equations for each satellite are

$$\rho_i = (x_u - x_i)^2 + (y_u - y_i)^2 + (z_u - z_i)^2 + b_u, \tag{2}$$

where the subscript i denotes each satellite and the subscript u denotes the users location and time (x, y, z are any convenient axes such as east, north, and up). Note that the satellite locations (x_i, y_i, z_i) are known from the navigation message on the signal. There are four unknowns in this equation (x_u, y_u, z_u, and b_u), and thus a minimum of four measurements is required to solve the equations. Generally, a direct solution is not computed, but rather the equations are linearized using a perturbation technique, and the position solution is computed using iterated least squares.

GPS Space Segment. The space segment of GPS is the satellite constellation (see Fig. 2) that consists of 24 or more vehicles in six orbital planes. The planes are inclined at 55° and are spaced 60° apart. There are four satellites in each of the orbital planes, but they are not evenly spaced. This was done to minimize the impact of any single satellite failure. Additionally, there are typically on-orbit spares in some of the six planes. The satellites are in a MEO orbit at a radius of 26,561.75 km (a mean equatorial altitude of 20,163 km). The orbits are almost perfectly circular and have an eccentricity of less than 0.01. The orbital period of these orbits is 12 hours of mean sidereal time (a mean sidereal day is the rotation of Earth to the same position with respect to inertial space, as opposed to a solar day, and is approximately four minutes shorter than a solar day). Thus, each GPS satellite repeats the same ground track, but passes the same location four minutes earlier each (solar) day.

The GPS payload consists of redundant atomic clocks, telemetry and control sections, and the signal generation subsystem. The atomic clocks are rubidium and/or cesium standards that typically have long-term stability of 1 part in 10^{13}

per day (or roughly a drift of 9 nanoseconds per day). The master control station monitors the atomic clock drift rates and models them as a quadratic,

$$\delta t = a_{f0} + a_{f1}(t - t_{0c}) + a_{f2}(t - t_{0c})^2 + \Delta t_r, \qquad (3)$$

where t_{0c} refers to the master clock, t is the satellite clock, and the various parameters a_{f0} through a_{f2} are parameters for the polynomial fit to the satellite clock drift. The last term, Δt_r, compensates for relativistic effects caused by the motion of the satellites and their position within the gravity well, which has the effect of making the satellites gain 38 microseconds per day. This is compensated for by setting the main satellite frequency standard (10.23 MHz) slower by 0.00455 Hz. GPS is the first operational system known to require a correction for relativistic effects. All of these parameters are sent in the navigation message.

The satellites' telemetry subsections are responsible for receiving the uploaded navigation data from the Master Control Station (MCS). The data is encrypted before upload to ensure than no spoofing can occur. Internal status and health is also monitored and relayed back to the MCS. The signal generation subsection is detailed later in the discussion of signal structure. Currently, the nominal signal power is set at a minimum of – 160 dBw for the Coarse Acquisition (C/A) code, – 163 dBw for the L1 P/Y code, and – 166 dBw for the L2 P/Y code, as shown in Table 2. Note that these power levels are well below the ambient noise level. From the satellites' location, Earth subtends an angle of approximately 14°. A user at the limb of Earth is significantly farther away than one directly under the satellites. To compensate for this greater "space loss," the antenna gain pattern on the GPS satellites is such that approximately 2.1 dB more gain is at the edges than at the boresight of the beam. The beam is also slightly wider than the 14° of Earth to allow non-GPS satellites on the other side of Earth to use GPS for positioning (9).

GPS Signal Structure. The PRN spread-spectrum coding that was originally pioneered for the Air Force 621B program contributes a great deal to the functionality of GPS. GPS uses a technique called *code division multiple access* (CDMA) such that each satellite broadcasts its message simultaneously on the same frequency, and yet the receiver can select each signal separately. The L1 signal is centered at 1575.42 MHz. This frequency is modulated with the satellite's civilian PRN code using a biphase shift key (BPSK) modulation, that is, the phase of the carrier is reversed to indicate a "chip" transition (the military signal is in quadrature and the composite signal is called QPSK). A "chip" is the BPSK analog of a bit, and in the L1C signal, is exactly 1540 carrier cycles long (or exactly 0.9775 μs). The C/A (e.g., L1C) PRN codes are 1023 chips long, which means that the code repeats every millisecond. Last, the code itself is inverted every 20 ms to indicate a bit transition on the navigation message that is broadcast at 50 bits per second. An illustration of the signal structure is shown in Fig. 7.

Table 2. **Minimum GPS Broadcast Power**[a]

Frequency	L1 (1575.42 MHz)	L2 (1227.60 MHz)
C/A	– 160 dBw	N/A
P-code	– 163 dBw	– 166 dBw

[a] The specification for both the C/A code and the P/Y code (military) is such that the minimum broadcast power is well below the noise floor of the in-band radiation. Using the correlation properties of the PRN codes, a GPS receiver can reconstruct the phase of the signal and use this for position and temporal information.

The GPS C/A PRN codes are very carefully chosen for specific properties. The first property is that they can be easily generated by using a simple shift register. This was an important consideration during the development stages of GPS but is no longer relevant to modern CDMA design. The two main advantages of PRN codes are the signal spreading and the correlation properties. The unique properties of the set of PRN codes are that they have very good code-to-code and cross-correlation (multiple access) properties, even in the presence of large Doppler offsets.

If a PRN code is multiplied and integrated (i.e., correlated) against a local copy of itself, it produces a large correlation coefficient when the start (or phase) of the two codes line up. If the codes are out of phase, it produces a very small value. Likewise, correlating one of the PRN codes with a different PRN code produces a very small value for all relative phases. The implication of this is that

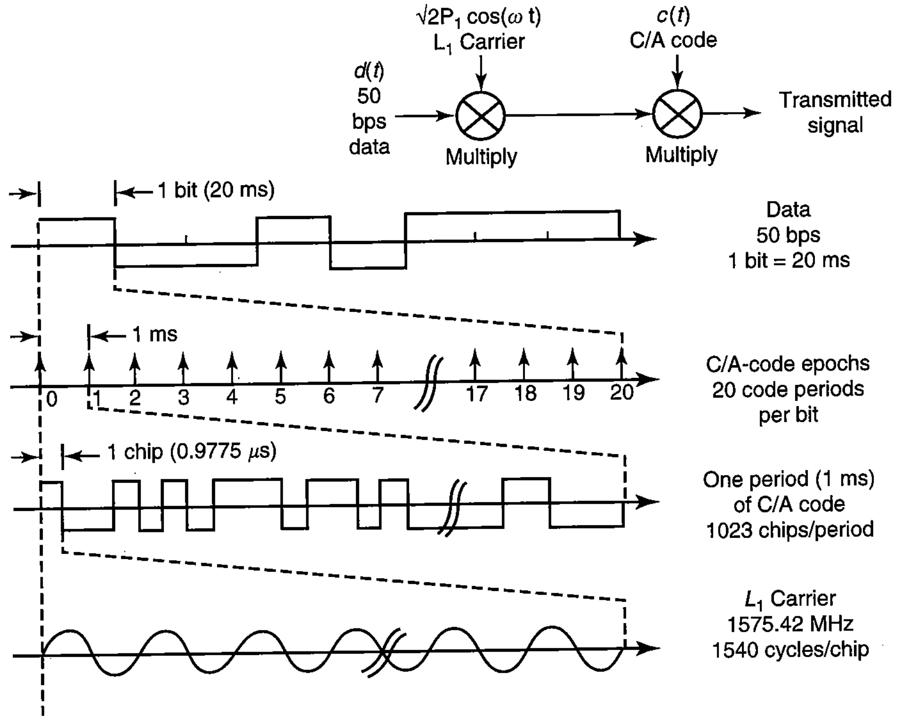


Figure 7. The GPS L1 signal structure is based on a carrier frequency at 1575.42 MHz. This frequency is modulated by biphase shift keying (BPSK) that uses phase reversal to indicate a changed "chip." Each chip is 1540 cycles wide (or 0.9775 μs). The code length is 1023 chips and repeats each ms. Last, every 20 ms, the entire code may invert to indicate a data bit reversal, modulated at 50 bits per second.

the phase of any given PRN signal within a receiver can be found by correlating a local copy at different phase offsets until a large signal is discovered. In this operation, all other PRN codes appear as noise. The worst case cross-correlation is −21.6 dB and is even lower at −23.8 if there is no Doppler offset. Pseudorange is the local clock reading (divided by the speed of light) at the start of the local code sequence when it is maximally correlated with the incoming signal (10).

Ground Control Segment. The GPS control segment consists of six or more monitoring stations around Earth, a Master Control Station (MCS), and upload ground-antenna stations. Each of the monitoring stations has a set of accurate atomic clocks and tracks both the code and carrier of each GPS satellite as it traverses overhead from horizon to horizon. The monitoring stations operate at both L1 and L2 frequencies to permit removing excess ionospheric delay. They also monitor atmospheric parameters such as temperature, atmospheric pressure, and humidity to permit estimating the tropospheric delay. By tracking the L-band carriers from horizon to horizon to a small fraction of a cycle (1% of an L2 carrier cycle is only 0.19 cm), a series of 15-minute averages is created and sent to the Master Control Station.

The Master Control Station receives the monitoring station tracking and ground antenna telemetry information and computes the current and predicted satellite clock offsets and satellite positions. It then converts this data to the navigation data formats described later. These rather complex satellite orbit/time filter estimating algorithms must also model the satellite solar radiation pressure, atmospheric drag on the satellite, Sun/Moon gravitational effects, including solid Earth and ocean tides, and Earth's geopotential model. Improved GPS satellite-to-satellite cross-link ranging data may also be used in the future. The navigation data are uploaded from several 10-m S-band ground antenna upload stations (11).

Navigation Data. The navigation data are encoded on the L1 C/A signal. This data message is transmitted at the rate of 50 bits per second and consists of a set of 6-second subframes (ten 30-bit words) and 30-second frames. The data encoded include the full ephemeris required to calculate the current satellite position, the satellite clock quadratic polynomial model and corrections to GPS time, almanac data used to position all the other satellites, and a hand-over-word for P/Y-code users. The almanac data allow a user to compute the rough positions of the satellite and thus narrow the search space both in terms of PRN codes and Doppler bins (12).

User Segment. The user segment or the GPS receiver is a very sophisticated digital signal tracking device that allows converting the faint signals from the GPS satellites into an accurate position solution. The GPS receiver must process the almanac (either stored or newly acquired) to generate a search space in terms of PRN codes and Doppler frequency bins. The incoming RF signal must be amplified, downconverted through an intermediate frequency (using a mixing process), and sampled into the digital domain. The PRN codes are correlated against the incoming digitized stream, and usually a delay lock loop (DLL) is implemented to keep the signal locked (13).

Once the signals are tracked, the corrections are applied to the raw pseudoranges, and the position and time bias are computed through an iterated least squares calculation. The positions are now reconverted to a useful coordinate frame such as latitude, longitude, and altitude. The original GPS "manpack" receivers were backpack-sized devices that cost more than $50,000 (see Fig. 8). GPS has benefited greatly from the semiconductor revolution, as has the typical consumer. A modern GPS receiver costs as little as $100 and is small enough to be embedded into at least one wristwatch. Additionally, the computer that calculates the position solution can support many additional features such as map displays and waypoint guidance at minimal additional cost.

GPS Ranging Errors. There are several error sources that can corrupt the pseudorange and carrier phase measurements, as shown in Fig. 9. Thermal noise and interference effects degrade the performance of a typical receiver. Over the years, receivers have improved in noise performance. The free electrons in the ionosphere cause a code delay but a carrier advance (the so called code–carrier divergence). The ionosphere also varies in total electron count (TEC) depending on the state of solar activity and time of day. Delays are also associated with the troposphere that are a function of the slant range and moisture content below an

Figure 8. The original GPS "Manpack" cost more than $50,000 each and was quite heavy. It did, however, satisfy the original mandate to produce an inexpensive device that could navigate. Modern-day receivers are much smaller and much less expensive. Today, one can buy both a watch and a cell-phone that has GPS built in. An inexpensive GPS receiver can be purchased for less than $100. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

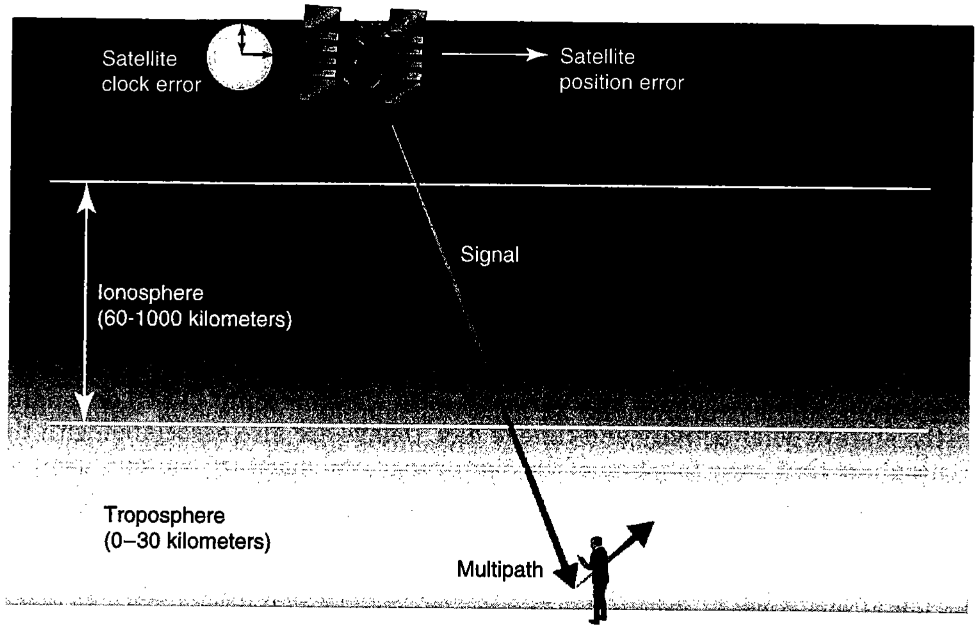


Figure 9. GPS ranging error sources. There are several different effects that can cause a ranging error in the GPS signal. Errors in either the satellite clock or orbital position (ephemeris) will cause errors. Additionally, both the ionosphere and troposphere cause delays in the signal. Last, multipath reflections of the signal can interfere with the original signal and distort the range information. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

altitude of 40 km. Errors in satellite position and clock directly cause errors in user ranging. Foliage can attenuate the signal, and more massive obstructions such as buildings or hills will block the signal completely. The latter is the origin of the urban canyon problem whereby GPS position is significantly degraded in cities that have tall buildings. User motion can cause the delay lock loops to be thrown off due to rapid changes in Doppler, though most terrestrial users will not experience such high rates of acceleration.

The largest error source (since selective availability has been turned off) is multipath. Multipath is the constructive or destructive interference with a reflected version of the signal that bounces off a nearby surface. Several techniques exist for multipath mitigation and are discussed in the next section.

GPS Error Analysis

To understand the potential of GPS, it is worthwhile to analyze the effect of the errors that occur when using it. In general, the errors are associated with measuring the range to the satellite. The ranges to four satellites must be processed to find the user's position, taking into account the locations of these satellites. Depending on geometry, the positioning error may be much higher than the typical ranging error. The ratio of the *positioning* error to the *ranging* error is called the geometric dilution of precision (GDOP). If all ranging errors are zero mean, uncorrelated, and have the same variance, the general relationship is

$$\sigma_P = \sigma_R \bullet \mathrm{DOP} \tag{4}$$

where

σ_P = positioning error
σ_R = ranging error
DOP = a multiplier due to geometry

The DOPs can be calculated by forming an array of unit vectors pointed at each satellite from the user's position, $\bar{e}_j$, using three convenient coordinate directions such as east, north, and up.

$$G = \left|\begin{array}{c|c} \bar{e}_1^T & 1 \\ \hline \bar{e}_2^T & 1 \\ \hline \bar{e}_3^T & 1 \\ \hline \bar{e}_4^T & 1 \end{array}\right| \tag{5}$$

The DOPs are then the square roots of the diagonal terms of the resulting 4 × 4 matrix:

$$\mathrm{GDOP} = (G^T G)^{-1} \tag{6}$$

and

$$\mathrm{Covariance(position)} = (G^T G)^{-1} \bullet \sigma_R^2. \tag{7}$$

The first three diagonal terms of GDOP refer to the coordinate directions selected above (e.g., east error factor, north error factor, and up error factor). The fourth diagonal term is the dilution for the range equivalent of the timing error. By dividing by the speed of light, one can change the value to the equivalent dilution in seconds (14).

The major sources of ranging error were discussed previously. Typical values are provided in Table 3. The typical dilution values (VDOP and HDOP) shown in Table 3 must be used with caution. If the satellite geometry is poor, it is not uncommon to find DOP multipliers of 10 or more. This is usually caused by a reduced number of satellites due to obstructions in the satellite line of sight. Typical causes are buildings, trees, and/or terrain. Modern receivers usually state the estimated error as part of the location message. Of course, the range of errors can be much greater than shown in Table 3, depending on age of update, atmospheric conditions, magnitude of multipath reflections, etc.

Table 3. **Typical GPS Ranging Errors for Various Sources**[a]

Error source	Typical root-mean-square ranging errors single-frequency code-tracking user		
	High	Low	Typical
Ephemeris data	3.0	0.7	1
Satellite clock	0.5	3.0	0.9
Ionosphere (after modeling)	6.0	2.0	4
Troposphere	2.0	0.3	0.5
Multipath	15.0	0.2	1.2
Receiver measurement and noise	1.0	0.2	0.5
User equivalent range error (UERE)			4.4
Vertical rms error with VDOP of 3.0 = 13.2 meters			
Horizontal rms error with HDOP of 2.0 = 8.8 meters			

[a] The typical dilution values (VDOP and HDOP) shown above must be used with caution. If the satellite geometry is poor, it is not uncommon to find DOP multipliers of 10 or more. This is usually caused by obstructions in the satellite line of sight due to buildings, trees, or terrain. Modern receivers usually state the estimated error as part of the location message.

As can be seen in Table 3, the largest typical error is for ionosphere transmission delays even after modeling for a single frequency receiver. Ionospheric delays are caused by the interaction of free electrons in the ionosphere with the radio signal. One of the key observations is that most of the delay through the ionosphere is proportional to the inverse square of the carrier frequency. Thus, a dual-frequency user can directly estimate the ionospheric delay and substantially reduce or eliminate this error. Currently, only military receivers are truly dual frequency. These receivers have a current user equivalent ranging error (UERE) less than 2 meters, when multipath errors are small. Note that currently scheduled improvements in the GPS signal include two new civil signals at L2 (1227.6 MHz) and L5 (1176.45 MHz). By using the new second and third civil signals, all users will be able to calibrate the ionospheric delay directly. This is the largest error for most users, so accuracy will improve substantially as this error category is reduced to near zero (15).

For a number of years, the DOD deliberately perturbed the timing signal on GPS (a technique called selective availability or SA). This increased the UERE to about four times the typical values shown in Table 3. Of course, this also resulted in positioning errors that were about four times larger (16). The extensive use of real-time differential calibration of these errors made this technique ineffective, and it was discontinued by Presidential order. Additionally, over the years, the ground station has become much more skilled at calibrating the errors in the signal-in-space (i.e., ephemeris and satellite clock errors). Improvements in predicting orbits and clock drifts, plus increased uplink frequency, have reduced signal-in-space errors from 6 meters to less than 2 meters. This progression can be seen in Fig. 10.

The next largest category of error in Table 3 is multipath error. Multipath error is the misleading interference of the delayed reflection of the GPS signal. In fact, this error will sometimes exceed the ionospheric error. Several techniques have been developed to mitigate the multipath problem. These range from better antenna designs whose gain patterns strongly attenuate signals coming from below the horizon to very narrow correlators that are immune to a large class of reflectors. Additionally, code measurements can be combined with carrier phase measurements that have a very different multipath response. As technology advances in receiver electronics and signal tracking, the receiver measurement noise will improve to the point of diminishing returns. Using dual-frequency receivers, multipath will be the dominant error source for GPS. Much of the future development in GPS receivers will be directed at eliminating the distortion from reflected signals (17).

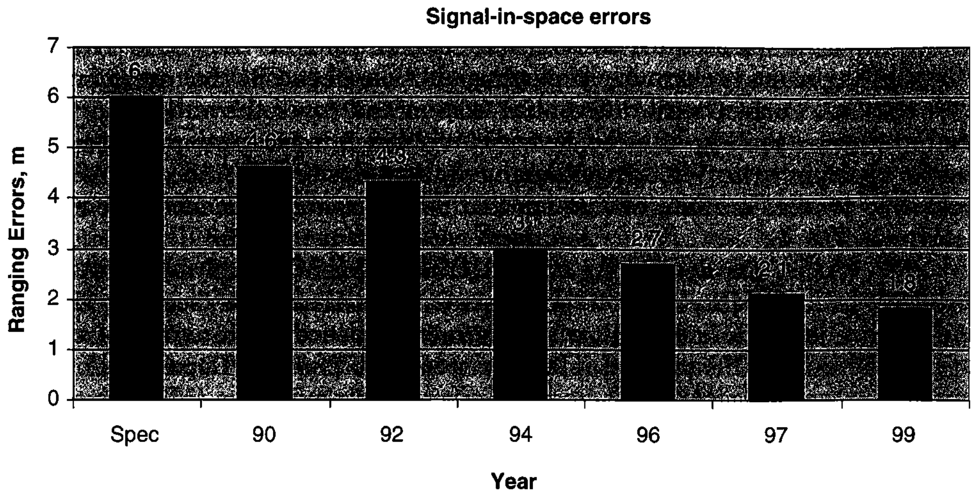


Figure 10. Signal-in-space errors have been steadily improving as ground segment operators have gained experience in orbit prediction and clock modeling. Additionally, the frequency of almanac updating has been increased. This has improved the signal-in-space error from the specification of 6 meters to less than 2 meters during a single decade. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

Differential GPS

One technique used to augment GPS is known as "differential." The basic idea is to locate one or more reference GPS receivers at known locations in users' vicinities and calibrate ranging errors as they occur (see Fig. 3). These errors are transmitted to users in near real time. The errors (or their negative, which are corrections) are highly correlated across tens of kilometers and across many minutes. Use of such corrections can greatly improve accuracy and integrity. Several large-scale differential networks have been deployed in the Unites States and elsewhere (18).

Overview of DGPS Systems. The U.S. Coast Guard (USCG) within the United States and the International Association of Lighthouse Authorities

(IALA) have deployed a marine beacon differential system internationally, known in the United States as National Differential GPS (NDGPS). The Army Corps of Engineers is currently deploying additional beacons that are compatible with the U.S. Coast Guard differential system and cover the entire continental United States (see Fig. 5). The Federal Aviation Administration (FAA) is currently deploying the Wide Area Augmentation System (WAAS). WAAS is intended to provide enroute navigation and nonprecision approaches for aviation users (see Fig. 4).

The FAA is also developing a Local Area Augmentation System (LAAS) for Category I, II, and III precision landing capability at airports (see Fig. 11). This will require local ground monitoring stations to ensure the integrity of the system in addition to the nominal reference receivers. The U.S. Department of Defense is currently developing a new Military Landing System (MLS) to operate like the LAAS system but will be used on aircraft carriers and at forward bases. The system, called the Joint Precision Approach and Landing System (JPALS), has already demonstrated fully autonomous carrier landing using a specially equipped Navy F/A-18 (19).

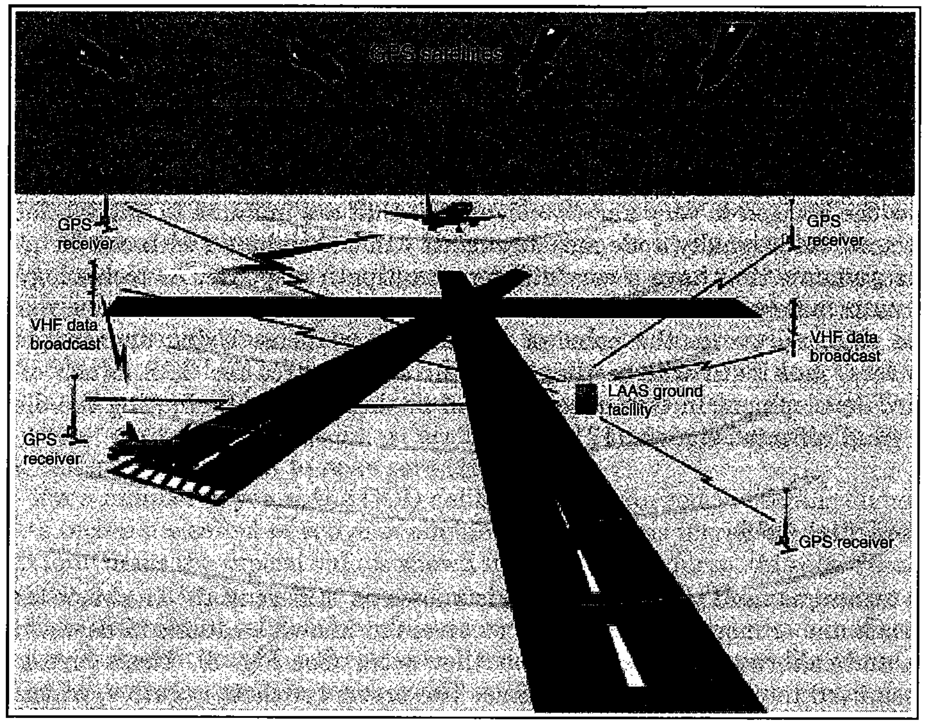


Figure 11. The LAAS system under current development by the FAA will provide precision approach capability using GPS. Due to the exacting requirements of Category II and III landings, the LAAS requires many cross-checks of the GPS system to ensure integrity. If one of these cross-checks fails, the time to alarm of the LAAS is specified at less than 6 seconds. This figure is available in full color at http://www.mrw.interscience.wiley.com/esst.

There are many additional private and international systems under development or deployed. Various private companies sell their own proprietary carrier phase differential GPS systems for use in such diverse areas as construction, surveying, and archeology. Commercial wide area corrections are carried by at least one commercial C-band satellite broadcast, and several oil companies have put their own differential stations on oil drilling platforms to ensure accurate positions for the helicopters and ships that service these platforms. The next subsections will further explain these examples.

National Differential GPS (NDGPS). NDGPS is a system that has been developed primarily for marine use. Both the U.S. and European equivalent systems use marine radio beacons transmitting in the 300 KHz band as communication links for GPS corrections; ranges are of the order of 100 to 200 kilometers. The applications are mostly for ships operating in coastal waters or upon navigable rivers. Typical accuracies are of the order of 1 to 2 meters horizontally; many commercial GPS sets now offer small additional radios to receive these corrections. Although the initial deployment has focused on U.S. Coast Guard applications, both the Army Corps of Engineers and the Department of Transportation are extending the NDGPS system to cover the entire continental United States. To expedite this full rollout, the NDGPS system will take over Ground Wave Emergency Network (GWEN) transmission stations from the U.S. Air Force because these stations are no longer necessary and were to be decommissioned. Figure 5 shows the current nominal coverage of the NDGPS network (20).

Wide Area Augmentation System (WAAS). The WAAS, developed by the U.S. FAA, is specifically designed to ensure integrity and improve accuracy for civil aviation users. GPS, augmented by WAAS, offers its capability for both enroute navigation and nonprecision approaches (NPA). Fig. 4 shows the general architecture of the WAAS system.

GPS satellite data is received and processed at widely dispersed Wide-Area Reference Stations (WRS) that are strategically located to provide redundant coverage across the required WAAS area. Data is forwarded to redundant Wide-Area Master Stations (WMS) that process the data from multiple WRSs to determine the integrity, differential corrections, and residual errors for each monitored satellite and each predetermined ionospheric grid point. The multiple WMSs are provided to eliminate single point failures within the WAAS network. The differential corrections are allocated to satellite, clock, and ionosphere, so they are called "vector" corrections as distinguished from normal scalar corrections. Information from all WMSs is sent to GEO Uplink Subsystems (GUS), where it is uplinked to the GEO satellites. The GEO satellites downlink this data to the users via a GPS signal at the L1 frequency. Communication between ground-based stations (WRSs, WMSs, and GUSs) and other systems is accomplished via the Terrestrial Communications Subsystem (TCS), which provides two independent networks for redundant data communications among WAAS components.

WAAS accomplished the goal of very large area coverage by using a small number of widely spaced ground stations. No additional hardware is required on the user equipment because the data are modulated on an L1 signal. Additionally, the presence of a GPS-like ranging signal on GEO WAAS satellites can improve the availability of the system if the WAAS signal-in-space has proper accuracy. Though the improvement in the positioning accuracy of WAAS is significant, more important is the bounding of worst case errors. Thus, the probability of hazardously misleading information (HMI) remains negligible ($<10^{-9}$). At the same time that WAAS bounds the worst case error, it does so without generating an unacceptable level of false alarms and keeping availability high at the nation's airports. As an added benefit, once the FAA declares WAAS operational, every single airport in the Unites States will potentially have NPA capability without installing any additional equipment at the airport (this will require new procedures).

WAAS has been under development since the mid-1990s and is currently in the final phase of deployment. The WAAS corrections, which are part of an additional GPS broadcast from two INMARSAT GEO satellites, are being extensively used. The typical accuracies for WAAS are shown in Table 4. The WAAS system is expected to be a boon to civil aviation in the United States, and both Europe and Japan are currently developing compatible nationwide augmentations for their own airspace (21,22).

Local Area Augmentation System (LAAS). Also being developed by the U.S. FAA is LAAS. It is designed to allow commercial aircraft landings down to Category II and possibly Category III. It is a highly redundant and reliable differential system that has several reference and monitoring stations and a very high standard of integrity. The LAAS system is meant to replace the current Instrument Landing System (ILS) at most large commercial airports (see Fig. 11). A Category III landing consists of a "zero-zero" landing (e.g., the visibility ceiling is at ground level and horizontal visibility is also zero). In practice, this means that the aircraft is landed by the autopilot. This is referred to as an "autocoupled" landing. Due to the automated nature of the landing, any landing system failure can be hazardous. This places an extremely high burden on LAAS to ensure that aircraft location is always within a well-defined error bound.

The LAAS system is designed with a very extensive set of cross-checks and verifications to ensure that no portion the system is operating outside its nominal parameters. These checks include validating the orbit of a given GPS satellite against a prediction based on the previous pass (from 12 hours before), checking the clock drift and both the range and range-rate of a rising satellite, plus many other checks. Time to alarm is vital for protecting any landing aircraft from misleading information and is specified at less than 6 seconds (23,24).

Table 4. **WAAS Projected System Accuracies**[a]

WAAS accuracies			
	50th percentile	95th percentile	99th percentile
Horizontal	1 meter	2 meters	5 meters
Vertical	2 meters	5 meters	10 meters

[a] The WAAS system was developed by the FAA to augment the GPS signal for civil aviation. The system is in its final stage of development, and many users are already using the corrections coming from the GEO satellites. WAAS excels in its ability to bound the worst case error and ensure that the probability of hazardously misleading information (HMI) remains very low while at the same time reducing the number of false alarms below the nuisance threshold.

Carrier Tracking Differential (CDGPS). Differential carrier tracking is another GPS technique that has been used by surveyors since the mid-1980s. By reconstructing the L-band radio-frequency (RF) carrier signal, a GPS receiver can attain tracking precisions of 1 to 10 millimeters. Specifically, a reference receiver (at a known location) measures the phase of the incoming carrier wave and transmits this information to a user. The user then compares this to the phase of the carrier wave received at the user's antenna. Because the wavelength of the L1 carrier is approximately 19 cm, a reasonable receiver can resolve this to 1% of the phase, or about 2 mm. Unfortunately, this is not accuracy. To attain equivalent accuracy, it is necessary to resolve the number of integer wavelengths along the RF path, that is, there are an unknown number of whole waves between the wave front arriving at the reference station and that at the user. Several techniques exist for resolving this integer cycle ambiguity. Satellite motion that can be exploited to do this differentially. This technique is referred to as real-time kinematic (RTK) GPS. When applied, this technique provides survey-level differential positioning whose accuracies are in millimeters. Thus one can locate an unknown point on the ground relative to a survey mark very rapidly and then maintain this accuracy as the user's receiver is moved. This is now being exploited for both construction survey and real-time, automatic, machine control (25).

The use of satellite motion can require some time to converge on the correct solution. An alternative for dual-frequency receivers is to set up a synthetic carrier wave by using the beat frequency of the L1 and L2 carriers together. The wavelength of the beat frequency is 86 cm, so the number of integer combinations to be searched in the position volume is typically much smaller and makes the problem more tractable. This technique is known as *wide laning*. Due to the advent of the two new civil frequencies on the block IIF satellites, users will be able to walk through a series of wide lanes to establish a carrier phase positioning solution very quickly (26).

Selected Applications

Applications of GPS have continued to multiply, as commercial and civil organizations apply creativity in using its capability. This section will not attempt to enumerate all current and future potential uses. Instead, selected examples will illustrate the revolutionary advances that have been made possible by this remarkable system. Many of the topics presented are at the cutting edge of current research and may yield profound improvement in our understanding of our world, as well as improved productivity and safety.

Survey and Crustal Motion. Until the advent of carrier phase differential GPS, measuring the relative distance or motion of large objects accurately over time required painstaking surveys using laser interferometry and tended to be one-dimensional. However, carrier phase differential GPS that can track 3-D relative positions down to millimeter levels across very long distances is revolutionizing the field of geomatics. Currently, experiments are underway that monitor the relative positions of the mountainsides of several volcanoes in the states of Hawaii and Washington. Previous attempts at these kinds of experiments proved difficult due to the requirement for consistent line-of-sight measurements using optical sensors. Data recorded by using survey-quality GPS receivers have detected bulging of the mountains and are providing insights that may one day enable scientists to predict volcanic eruptions (27).

Similarly, hundreds of GPS receivers have been placed along fault lines throughout California and other parts of the world to validate theories about plate motion and gain valuable information on preconditions to earthquakes. Again, research in this area is still in its infancy, but it has never before been so economical or in some cases even possible, to measure the distance across large geographic features down to the millimeter level. At this time, data are being gathered to validate crustal motion models that will certainly lead to refinements in these models (28).

Aviation. The aviation industry has been an early adopter of GPS technologies and remains at the forefront of developing and implementing new GPS advances. In the early 1990s, a prototype GPS landing system for Category III (zero ft ceiling, zero miles visibility) was developed and demonstrated by Stanford University under an FAA grant. This system used carrier phase differential GPS to ensure a correct position. To resolve the integer cycle ambiguities quickly and robustly, two ground transmitters that broadcast GPS-like signals were used to augment the system. These "pseudolites" exhibited a large change in Doppler shift due to the rapid geometric change. The resulting system demonstrated more than 100 autocoupled landings at Crows Landing Airport in California; data were independently validated by using the Crows Landing laser tracker. The data showed an accuracy of better than 0.5 meter (3-D) in the final phase of landing (29).

During one of the autocoupled landings, a satellite upload from the Master Control Station caused the satellite to interrupt its transmission for approximately 1 millisecond. The Stanford system detected this glitch in the space segment and called off the landing in real time.

Though the FAA has not yet declared GPS operational as a *precision* navigation aid, most General Aviation and Commercial pilots use GPS as a backup system for navigation. Additionally, modern aviation GPS units are programmed with a full aviation database and can notify the user of airspace violations. In an emergency, these units can guide the pilot to the closest airport at the touch of a button.

GPS, as a full 13-state sensor for an aircraft, provides a powerful suite of information at a relatively low cost. Combined with inexpensive computer graphics, a synthetic "out-the-window" perspective display can be used to improve vastly the presentation of critical data to the pilot (30). The futuristic vision of tunnels-in-the-sky for improved navigation is being tested today in various laboratories around the world. Pilots who have experimented with these systems report a much reduced workload and greater situational awareness (31). The potential to reduce controlled flight into terrain (CFIT) could save many lives currently lost due to such accidents. Likewise, if all other aircraft are prominently displayed, it can reduce midair collisions. These displays have also shown great promise in enabling closely spaced parallel approaches (CSPA) in inclement weather (32). This alone can save the United States billions of dollars in runway expansions and avoiding environmental impact that such construction would have on surrounding areas.

Vehicle Tracking. The so-called "urban canyon" can adversely affect GPS, but vehicle tracking remains a very important application. During urban canyon outages, most vehicle tracking systems use inertial augmentation to provide a position solution. Commercial companies have great interest in knowing where their equipment is currently located, and GPS provides an ideal answer. Many cities now have buses equipped with GPS receivers and radio transmitters. Each bus stop has a display of the current location of the next bus, and an estimate of the time to arrival. Likewise, many cities have GPS equipment on their emergency service vehicles to manage the response better. This has been shown very effective in reducing response time and managing these scarce resources during a large-scale disaster (33).

Vehicle tracking yields a great competitive advantage to a corporation. In one case, a cement company in Guadalajara, Mexico, would send fully loaded cement trucks into the city every morning, even though orders had not yet been placed. Using simple radio communication, this company responded to orders in less than half the time of any of its competitors. Though several trucks of cement would go to waste at the end of each day, within a short time, this company dominated the cement delivery market (34).

Last, law enforcement officials have been able to use GPS to increase their effective manpower by remotely monitoring suspects. After obtaining a court order allowing them to install a GPS receiver surreptitiously on a suspect's car, Seattle police were able later to reconstruct the time and path of the location during a 2-week period, without alerting the suspect to the surveillance. This information led directly to evidence that convicted the suspect.

Precision Munitions. No discussion of GPS would be complete without a brief discussion of military applications. In spite of its explosive use for many civil applications, GPS was designed primarily as a military system, and to continue development, GPS must fulfill its primary mission. Several military applications for GPS were developed in recent years. An example is the JDAM. This precision-guided munition has demonstrated a battlefield accuracy of less than 10 meters. The trend in the future is to reduce the explosive warhead size of these kinds of munitions, which can be done only if the guidance system is capable of pinpoint accuracy (35).

On purely defensive military applications, the DOD recently deployed a Combat Survivor/Evader Locator (CSEL) radio for servicemen/women. This radio allows downed pilots to relay their positions to rescuers directly to enable rapid rescue and minimal exposure to hostile forces. The CSEL replaces four different individual devices with a single integrated package (36).

Space Applications. Some of the most innovative and unusual applications of GPS occur in the area of Earth sensing and space applications. Low Earth orbiting satellites can use GPS to measure both position and attitude. Precise satellite data can be used to refine gravitational models of Earth, and can be used as a sensor for attitude control. A soon-to-fly satellite experiment, the Gravity Probe B (GPB), uses very precise spherical gyroscopes to yield a quantitative measurement of Einstein's theory of relativity. For the experiment to be valid, GPB needs to fly a "drag-free" polar orbit to within 100 meters. GPS is used to provide guidance information to position the orbit of the satellite initially (37). Last, one of the most unusual applications of GPS is using the reflection of GPS signals from waves at sea to detect wave height in the open ocean (38).

Relationships to Galileo

Galileo is the European version of GPS. The European Union is committed to building a 30-satellite civil space-based navigation system at an estimated cost of 3.4 billion euros. The initial funding of 547 million euros is intended to fund the study and development phase, which is expected to take approximately 3 years. Galileo will be an entirely civil system that promises to be independent, but interoperable with the civil components of GPS.

Several outstanding issues must be resolved before Galileo becomes operational (planned for 2008). The most crucial is that the Galileo signals not interfere with any of the GPS signals. Ideally, Galileo would use a compatible geodetic reference frame and time base calibrated to GPS. This would present the Galileo satellites as an augmentation to the GPS constellation or conversely the GPS constellation as an augmentation to Galileo. Barring this level of interoperability, it is likely that Galileo will use a time base and geodetic reference frame distinct from GPS but one that can be easily translated back and forth between the two systems if real-time data are available. The exact configuration of the Galileo system is not yet certain and is the subject of current diplomatic negotiation between the United States and the European Union (39).

Future Improvements

The first block II-R GPS satellite was launched in 1997. Though the later versions of block IIs will be a bridge to a future GPS system, known as GPS III, the next generation of GPS is still being defined. Future improvements in the GPS system are driven by competing civil and military requirements. All users desire more signal power to ensure resistance to interference and/or jamming. In the last decade, GPS has become essential to virtually all DOD operations. International constraints on RF spectrum availability dictate that improvements remain within the radio navigation bands. On the civil side, the expectation has become that GPS will remain continuously available across the globe for the foreseeable future. Civilian users are urgently requesting the second and third frequencies to calibrate ionospheric delays and provide a backup if the L1 signal is jammed.

Several key advances are planned for the end of the block II series of satellites. The most important are two additional signals on the II-RMs and three on the II-Fs. The first additional signal is a replica of the C/A code but at the L2 frequency. This will allow direct measurement of ionospheric errors for civilian users. Military users will have a new split spectrum code (called M-code) on both L1 and L2. This code has the advantage of transmitting most of its power in the nulls of the C/A code, maximizing spectral separation. The signal modernization is shown in Fig. 6.

The II-Fs will include yet another civil signal at L5 (1176 MHz). This signal is intended to be a higher accuracy signal, which implies a higher chipping rate and a longer code sequence. Likely, it will include an unmodulated channel to enable much longer integration time for superior noise rejection. Other technical advances for the late II-Fs include intersatellite communication, as well as improvements in the rubidium/cesium clocks on board. Likewise, upgrades in the ground station facilities will reduce the errors in ephemeris predictions. For GPS III, the need for further increases in M-code power will probably lead to a spot beam of about 1000 kilometers (40).

Though all specifics of the GPS III concept are still to be determined, the United States intends to continue to provide and improve on a worldwide continuously available, precise, navigation signal that is free to all of the world. GPS III will undoubtedly continue in that tradition and provide a yet more robust and more accurate system of positioning on a global scale.

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