Chapter 25

GLOBAL POSITIONING SYSTEM

System Description

The Navigation Satellite Time and Ranging (NAVSTAR) Global Positioning System (GPS) is a space-based satellite radio navigation system developed by the U. S. Department of Defense (DoD). GPS receivers provide land, marine, and airborne users with continuous three-dimensional (3D) position, velocity, and time data (PVT). This information is available free of charge to an unlimited number of users. The system operates under all weather conditions, 24 hours a day, anywhere on Earth. The Union of Soviet Socialist Republics developed a similar system that is generally not used because it is a duplication of the NAVSTAR function.

GPS System Design

The GPS system consists of (1) the space segment, (2) the control segment, and (3) the user segment.

Space Segment.—The space segment consists of a nominal constellation of 24 operational satellites (including 3 spares) that have been placed in 6 orbital planes 10,900 miles (20,200 kilometers [km]) above the Earth's surface. The satellites are in circular orbits with a 12-hour orbital period and an inclination angle of 55 degrees. This orientation provides a minimum of five satellites in view at any time anywhere on Earth. Each satellite continuously broadcasts two low-power, spread-spectrum, RF Link signals (L1 and L2). The L1 signal is centered at 1575.42 megahertz (MHz), and the L2 signal is centered at 1227.6 MHz.

Control Segment.—The control segment consists of a Master Control Station (in Colorado Springs) and a number of monitor stations at various locations around the world. Each monitor station tracks all the GPS satellites in view and passes the signal measurement data back to the Master Control Station. Computations are performed at the Master Control Station to determine a precise satellite ephemeris and satellite clock errors. These data are then uplinked to the individual satellites and, subsequently, rebroadcast by the satellite as part of a navigation data message.

User Segment.—The user segment is all GPS receivers and their application support equipment such as antennas and processors. This equipment allows users to receive, decode, and process the information necessary to obtain accurate position, velocity, and timing measurements. These data are used by the receiver's support equipment for specific application requirements.

GPS Basic Operating Concepts

Satellite Signals.—The satellites transmit their signals using spread-spectrum techniques that employ two different spreading functions: a 1.023-MHZ coarse/acquisition (C/A) code on L1 only and a 10.23-MHz precision (P) code on both L1 and L2. The two spreading techniques provide two levels of GPS service: Precise Positioning Service (PPS) and Standard Positioning Service (SPS). SPS uses C/A code to derive position, while PPS uses the more precise P-code (Y-code).

C/A Code.—The C/A code is a 1,023 bit nonrepeating code sequence with a clock rate of 1.023 MHZ. The satellite repeats the code once every millisecond. Each satellite is assigned a unique C/A code that is chosen from a set of codes known as Gold Codes.

P(Y)-Code.—The P-code consists of a 2.36e+14 bit nonrepeating code sequence with a clock rate of 10.23 MHZ. The entire code would take 267 days before a repetition occurs; however, each satellite is assigned a unique 1-week segment of this code that restarts every Saturday/Sunday midnight.

The P-code has a number of advantages over C/A code. (1) The P-code rate is 10 times faster; therefore, the wavelength is 1/10th as long, giving the P-code a much higher resolution. (2) The higher rate spreads the signal over a wider frequency range (see figure 25-1). This frequency spreading makes the P-code much more difficult to jam. (3) By encrypting the P-code (creating Y-code), the receiver is not susceptible to spoofing (false GPS signals intended to deceive the receiver).

The drawback of P-code is that it is relatively difficult to acquire because of its length and high speed. For this reason, many PPS receivers first acquire C/A code, then switch over to the P(Y)-code. Y-code is an encrypted

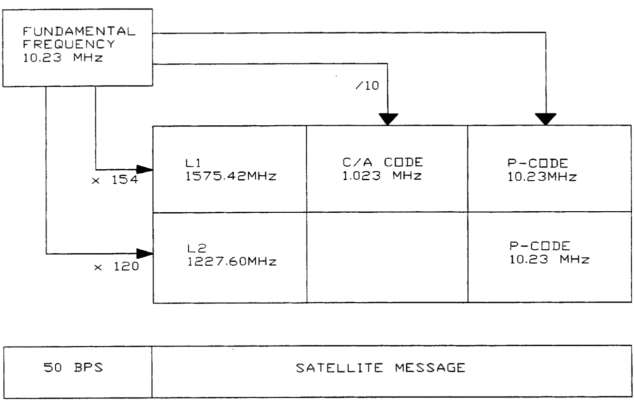

Figure 25-1.—Satellite signal structure.

version of P-code that is used for anti-spoofing (A-S). Because of the similarity of these two codes, they are referred to collectively as P(Y)-code.

Navigation (NAV) Message

Superimposed on both the P-code and the C/A code is a navigation (NAV) message containing satellite ephemeris data, atmospheric propagation correction data, satellite clock-bias information, and almanac information for all satellites in the constellation.

The navigation message consists of 25 1,500-bit frames and is broadcast at 50 bits per second. It takes 30 seconds to receive a data frame or 12.5 minutes to receive all 25 data frames. Each satellite repeats its own ephemeris data and clock bias every frame along with a portion of the almanac. The receiver will receive the critical acquisition information within 30 seconds, but a full almanac will require 12.5 minutes to download.

Signal Acquisition.—The GPS satellites use Bi-Phase Shift Keyed (BPSK) modulation to transmit the C/A and P(Y)-codes. The BPSK technique involves reversal of the carrier phase whenever the C/A or P(Y)-code transitions from 0 to 1 or from 1 to 0.

To the casual observer, the very long sequence of ones and zeros that make up the C/A and P-codes appears random and blends into the background noise. For this reason, the codes are known as pseudo-random noise (PRN).

In actuality, the C/A and P-codes generated are precisely predictable to the start time of the code sequence and can be duplicated by the GPS receiver. The amount the receiver must offset its code generator to match the

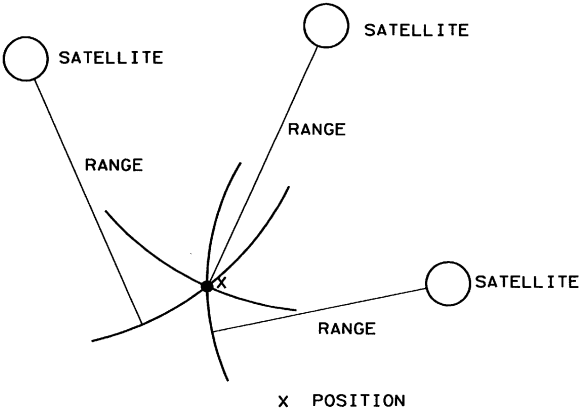

Figure 25-2.—Satellite ranging intersections.

incoming code from the satellite is directly proportional to the range between the GPS receiver antenna and the satellite.

By the time the spread-spectrum signal arrives at the GPS receiver, the signal power is well below the thermal noise level. To recover the signal, the receiver uses a correlation method to compare the incoming signals with its own generated C/A or P(Y) codes. The receiver shifts its generated code until the two codes are correlated.

Satellite Ranging.—The receiver continuously determines its geographic position by measuring the ranges (the distance between a satellite with known coordinates in space and the receiver's antenna) of several satellites and computes the geometric intersection of these ranges. To determine a range, the receiver measures the time required for the GPS signal to travel from the satellite to the receiver antenna. The resulting time shift is multiplied by the speed of light, arriving at the range measurement.

Because the resulting range measurement contains propagation delays caused by atmospheric effects as well as satellite and receiver clock errors, the measurement is referred to as a "pseudorange." A minimum of four pseudorange measurements are required by the receiver to mathematically determine time and the three components of position (latitude, longitude, and elevation). The solution of these equations may be visualized as the geometric intersections of ranges from known satellite locations (see figure 25-2). If one of the variables, such as elevation, is known, only three satellite pseudorange measurements are required for a PVT solution, and only three satellites would need to be tracked.

GPS Accuracy

GPS accuracy has a statistical distribution that depends on a number of important factors, including dilution of precision (DOP) satellite position and clock errors, atmospheric delay of the satellite signals, selective availability (SA), signal obstruction, and multipath errors.

Dilution of Precision

Geometric Dilution of Precision (GDOP) is a measure of the amount of error due to the geometry of the satellites. The errors in the range measurements that are used to solve for position may be magnified by poor geometry. The least error results when the lines of sight have the greatest angular separation between satellites.

There are four other DOP components that indicate how the geometry specifically affects errors in horizontal position (HDOP), vertical position (VDOP), position (PDOP), and time (TDOP). DOPs are computed based on the spatial relationships between the satellites and the user and vary constantly due to the motion of the satellites. Lower DOPs mean more accurate estimates. A PDOP less than six is necessary for accurate GPS positioning.

Satellite Position and Clock Errors

Each satellite follows a known orbit around the earth and contains a precise atomic clock. The monitor stations closely track each satellite to detect any errors in the orbit or the clock. Corrections for errors are sent to each satellite as ephemeris and almanac data. The ephemeris data contain specific position and clock correction data for each satellite while the almanac contains satellite position data for all satellites. The NAV set receives the ephemeris and almanac data from the satellites and uses these data to compensate for the position and clock errors when calculating the NAV data.

Atmospheric Delay of Satellite Signals

Electromagnetic signals (such as GPS signals) travel at the speed of light, which is always a constant in a vacuum but not in the atmosphere. There are two layers of the Earth's atmosphere that affect satellite signals, the ionosphere and the troposphere.

The ionosphere is a 90-mile (150-km) thick layer of the upper atmosphere in which ultraviolet radiation from the sun has ionized a fraction of the gas molecules, thereby releasing free electrons (ions). The shape of the ionosphere and its electron density varies with latitude, time of day, time of year, number of sunspots, solar flares, and other cosmic activity. The magnitude of the error caused by ionospheric effects can translate to a position error as large as 130 ft (40 m).

The troposphere is the dense, humid layer of atmosphere near the surface of the Earth. This layer refracts the satellite signals in proportion to the humidity and density of the air. The magnitude of the tropospheric error can be as small as 8 ft (2.3 m) at the zenith, or as large as 65 ft (20 m) at 10 degrees above the horizon.

There are two ways to compensate for the atmospheric delays: modeling and direct measurement. The ionospheric and tropospheric delays are inversely proportional to the square of the frequency. If a receiver can receive L1 and L2 frequencies, it can measure the difference between the two signals and calculate the exact atmospheric delay.

Most receivers currently use mathematical models to approximate the atmospheric delay. The tropospheric effects are fairly static and predictable, and a model has been developed that effectively removes 92-95 percent of the error. This reduces the total two-dimensional (2D) position error caused by the troposphere to around 8 ft (2.0 m).

The ionosphere is more difficult to model because of its unusual shape and the number of factors that affect it. A model has been developed that requires eight variable coefficients. Every day, the control segment calculates the coefficients for the ionospheric model and uplinks them to the satellites. The data are then rebroadcast in the NAV messages of the C/A and P(Y)-codes. This model can effectively remove 55 percent of the ionospheric delay, reducing the total 2D position error caused by the ionosphere to around 25 ft (7.5 m).

Selective Availability and Anti-Spoofing

GPS satellites provide two levels of navigation service: Standard Position Service and Precise Position Service.

SPS receivers use GPS information that is broadcast in the clear and is available to anyone in the world. This information may contain built-in errors that limit the accuracy of the receiver. This is a security technique called Selective Availability (SA). These SA errors are variable. In normal conditions, the U.S. Government guarantees that these errors do not exceed 100 m horizontal, 140 m vertical, and time accuracy of 340 nanoseconds, 95 percent of the time. There are times when an SPS receiver error exceeds these limits. SPS receivers are for civil use, and SA may or may not be on.

PPS receivers use the same information as SPS receivers. PPS receivers also read encoded information that contains the corrections to remove the intentional SA errors. Only users who have crypto keys to decode this information get the PPS accuracy. U.S. Government agencies and some Allies are authorized to have these crypto keys. A receiver with valid crypto keys loaded and verified is a PPS receiver.

To protect authorized users from hostile attempts to imitate the GPS signals, a security technique called anti-spoofing is also used. This is an encrypted signal from the satellites that can be read only by PPS receivers. SPS receivers are not capable of using anti-spoofing. A receiver with valid crypto keys loaded and verified reads this encrypted signal and operates in a spoofing environment.

GPS Signal Obstruction

Normal operation of the GPS receiver requires undisturbed reception of signals from as few as four satellites (in normal 3D mode) or three satellites in fixed-elevation mode. The signals propagating from the satellites cannot penetrate water, soil, walls, or other similar obstacles.

The antenna and the satellites are required to be in "line-of-sight" with each other. GPS cannot be used for underground positioning in tunnels, mines, or subsurface marine navigation. In surface navigation, the signal can be obscured by buildings, bridges, trees, and other matter that might block an antenna's line-of-sight from the GPS satellites. In airborne applications, the signal can be shaded by the aircraft's body during high banking angles. For moving users, signal shading or temporary outages are generally transitory and should not degrade the overall positioning solution.

The GPS receiver uses five channels to minimize the effects of obstruction. During normal operation, four channels track the four primary GPS satellites while the fifth channel tracks the remaining visible satellites and recovers the ephemeris data for each satellite. If one or more of the primary satellites are obscured, the receiver contains the data to support rapid acquisition of alternative satellites.

If only three satellites can be tracked, receivers may feature an “Elevation Hold” mode and continue to navigate as previously noted. The accuracy of the PVT in this mode will not be greatly affected unless the elevation changes. The receiver will use either the last computed elevation or an elevation provided by the user or host system. The accuracy of the “Elevation Hold” mode depends on the accuracy of the elevation provided to the receiver.

Multipath Interference

Multipath errors result from the combination of data from more than one propagation path. These errors distort the signal characteristics of the range measurements and result in pseudorange errors. These errors depend on the nature and location of a reflective surface peculiar to each user location. The effects are less detrimental for a moving user because small antenna movements can completely change the multipath characteristics.

The receiver is designed to reject multipath signals. First, the active patch antennas are designed to have a sharp gain roll-off near the horizon while providing nominal gain for the primary satellite signal. Since most multipath signals are reflected from ground structures, they tend to be attenuated. Second, the antenna is right-hand polarized. When a right-hand polarized GPS signal is reflected off a conductive surface, the signal becomes left-hand polarized and rejected by the antenna. The receiver also has hardware and software designed to reduce the effects of any multipath interference errors.

Differential GPS

Differential GPS (DGPS) may be used to eliminate the effects of SA and correct certain bias-like errors in the GPS signals. A Reference or Base Station Receiver measures ranges from all visible satellites to its surveyed position. Differences between the measured and estimated ranges are computed and saved for post processing or transmitted by radio or other signals to differential equipped receivers. Sub-meter to centimeter position accuracy is possible using local base station differential GPS.

Quality of Measurement

The accuracy with which positions are determined using GPS depends on two factors—satellite geometry and user measurement accuracy.

Satellite Geometry

Satellite geometry effects on specific position solutions can be expressed as dilution of precision. DOP is used to describe the contribution of satellite geometry to total positioning accuracy. An ideal satellite constellation would not dilute the positioning accuracy.

Ideal Satellite Constellation

The term, “current satellite constellation,” refers to the satellites being used in the current position solution. When the current satellite constellation geometry is ideal, the DOP value is 1. This means the current satellite constellation contributes a “dilution factor” of 1 to positioning accuracy. Most of the time, the satellite geometry is not ideal, which means the current satellite constellation geometry "dilutes the precision" of the positioning accuracy. As the satellite constellation becomes less ideal, the adverse effect on positioning accuracy is greater. The dilution will change over time as satellites travel along their orbits, as different satellites are used to solve for GPS position, and as the user moves.

DOP Effects

The effect of satellite geometry is not equally distributed in all three positional vectors (x, y, and z in Earth-centered, Earth-fixed coordinates). Several DOP related values are commonly used. Table 25-1 shows expected values for HDOP, VDOP, and others. The range given for

Table 25-1.—Expected values of dilution of precision

DOP	Description	68-percent probability of obtaining	95-percent probability of obtaining
HDOP	Horizontal DOP is the satellite geometry factor in the 2D horizontal position solution.	1.50	1.78
VDOP	Vertical DOP is the satellite geometry factor in the vertical position (elevation) solution.	2.08	2.70
PDOP	Positional DOP is the satellite geometry factor in the 3D position solution.	2.56	3.23
$\text{PDOP} = \sqrt{\left(\text{HDOP}^2 + \text{VDOP}^2\right)}$			
TDOP	Time DOP is the satellite geometry factor in the time solution.	N/A	N/A
HTDOP	Horizontal and time DOP is the satellite geometry factor in the 2D horizontal position and time solutions. HTDOP = SQRT ($\text{HDOP}^2 + \text{TDOP}^2$)	N/A	N/A
GDOP	Geometrical DOP is the satellite geometry factor in the 3D position and time solutions. GDOP = SQRT ($\text{HDOP}^2 + \text{VDOP}^2 + \text{TDOP}^2$)	2.79	3.61

VDOP, HDOP, GDOP, and PDOP assumes a 5-degree antenna mask (signals 5 degrees or more above the horizon) and a 24 satellite constellation.

Unique user conditions, such as more than 5 degrees of antenna masking (e.g., in deep canyons), satellite outages, and poor constellation choice may result in a degraded DOP.

Quality Indicators

The indicators of solution quality are computed based on several things. These include uncertainties in receiver measurement processes, current satellite constellation geometry, and errors as reported by the satellites, such as the User Range Accuracy (URA) index. There are different measures of quality. A quality indicator must be selected based on the requirements of the application and how meaningful that measure will be. Some measures of quality indicators are shown below.

Circular Error Probable.—Circular Error Probable (CEP) is an estimate of horizontal accuracy that expresses the radius of a circle in the horizontal plane that will contain at least 50 percent of the GPS 2D positional solutions. CEP is generally expressed in meters; a smaller value indicates a higher quality 2D position solution. CEP is not desirable as a quality measure for navigation systems because a 50-percent probability is too small. This measure can be useful in some applications, for example, a bombing run where a better than 50-percent chance of hitting a target is required. CEP is not available from all GPS units. However, CEP may be estimated by the following equation.

$$CEP = 0.8323 * EHE$$

EHE is the expected horizontal error.

R95.—R95 is similar to CEP except that the circle contains at least 95 percent of the GPS 2D positional solutions. R95 is generally expressed in meters, and a smaller value indicates a higher quality 2D position. R95 is better than CEP as a measure for navigation systems because a 95-percent probability is more commonly associated with navigation requirements. R95 is not available from all GPS units. However, it may be estimated by the following equation.

R95 = 1.731 * EHE

Spherical Error Probable.—Spherical error probable (SEP) is an estimate of 3D accuracy that is the radius of a sphere that will contain at least 50 percent of the GPS 3D positional solutions. SEP is generally expressed in meters, and a smaller value indicates a higher quality 3D position solution. SEP is not desirable as a quality measure for navigation systems for the same reason that CEP is not; a 50-percent probability is too small. A spherical model of errors is not well suited to the GPS model because error probabilities in the horizontal plane are of a smaller scale than those in the vertical plane (compare HDOP to VDOP). This leads to more of a football shaped error distribution than a spherical distribution. SEP is not available from all GPS units.

Expected Position Error.—Expected position error (EPE) is a 1-sigma calculation of 3D position solution estimate of error. EPE is expressed in meters, and a smaller EPE indicates a higher quality position solution. Similarly computed values are often referred to, including:

EHE, Expected Horizontal Error
(1-sigma estimate of 2D error)

EVE, Expected Vertical Error
(1-sigma estimate of one-dimensional error)

$$EPE = \sqrt{\left(EHE^2 + EVE^2\right)}$$

EPE is one of the best available indicators of quality for navigation systems.

EPE can also be output as Figure of Merit (FoM). (See below.)

Root Mean Square.—Root Mean Square (RMS) is a 1-sigma calculation of error in position. Horizontal RMS is equivalent to EHE, vertical RMS is equivalent to EVE, and 3D RMS is equivalent to EPE.

The above is true only if the mean values of the error components are zero or the biases of the errors can be independently determined and removed.

Figure of Merit.—Figure of Merit (FOM) is an expression of EPE, as shown in table 25-2.

From a historical perspective, FOM was created at the inception of GPS to provide users with a simple and quick method of indicating the solution accuracy; it is still widely used in many military applications today. It does not have the granularity to take advantage of the significant improvements in accuracies that may be achieved today. FOM is available from some GPS units on the display.

Table 25-2.—FOM related to EPE

FOM	EPE (meters)
1	< 25
2	< 50
3	< 75
4	< 100
5	< 200
6	< 500
7	< 1,000
8	< 5,000
9	≥ 5,000

Expected Time Error.—Expected Time Error (ETE) is a calculation of time error that is computed similarly to EPE. ETE is a 1-sigma estimate of time solution error. ETE is expressed in seconds, and a lower ETE indicates a higher quality time solution. Some GPS units calculate and output EPE in the form of Time Figure of Merit.

Time Figure of Merit.—Time Figure of Merit (TFOM) is an expression of ETE as shown in table 25-3.

Table 25-3.—TFOM related to ETE

TFOM	ETE
1	< 1 nanosec
2	< 10 nanosec
3	< 100 nanosec
4	< 1 microsec
5	< 10 microsec
6	< 100 microsec
7	< 1 millisec
8	< 10 millisec
9	≥ 10 millisec

User Measurement Accuracy

Several factors are involved in the receiver's ability to accurately measure the distance to the satellites. The most significant factors in user measurement accuracy are space and control segment errors, atmospherics, and user equipment (UE) errors. These errors are generally grouped together and referred to as User Equivalent Range Error (UERE).

User Equivalent Range Error

User Equivalent Range Error represents the combined effect of space and control segment errors (satellite vehicle position [ephemeris] and clock errors), atmospherics (ionospheric and tropospheric), and user equipment errors (receiver measurement uncertainties). UERE cannot be broadcast by the satellites and can be estimated only at the receiver. The point that sets UERE apart from other measures of error is that UERE does not take into account any satellite geometry effects, such as HDOP or VDOP. Table 25-4 shows a typical error budget for a P(Y)-code GPS receiver.

Table 25-4.—Typical GPS receiver error budget

Accuracy factor	Error
Space and control segment	4.0 m
Ionospheric	5.0 m
Tropospheric	2.0 m
Receiver noise	1.5 m
Multipath	1.2 m
Miscellaneous	0.5 m
$\mathbf{UERE} = \sqrt{\left(4^2 + 5^2 + 2^2 + 1.5^2 + 1.2^2 + 0.5^2\right)}$	7.0 m

Space and Control Segment Errors

Satellites provide an estimate of their own satellite position and clock errors. Each satellite transmits an indication of these errors in the form of User Range Accuracy (URA).

URA is a value transmitted by each GPS satellite that is a statistical indicator (1-sigma estimate) of ranging accuracies obtainable from that satellite. URA includes all errors that the space and control segments are responsible for—for example, satellite clock error and SA error. URA has very coarse granularity, however.

The URA value is received in the form of an index related to URA as shown in table 25-5.

The URA index broadcast by each satellite will change over time. In practice, the control segment will upload correction data to each satellite at least once every 24 hours. When a satellite first receives its upload, it should have a very low URA index. The amount of error will increase over time, because of things such as satellite clock drift, and the URA index for that satellite will grow. Some satellites' URA index will grow more rapidly than others.

In practice, authorized PPS users should expect to see URA index values in the range of 0 to 5. More commonly, values of 2-4 should be expected. The values depend on the length of time since the last control segment upload to that satellite.

Table 25-5.—URA index and values

URA index	URA (meters)
1	0.00 < URA <= 2.40
2	2.40 < URA <= 3.40
3	3.40 < URA <= 4.85
4	6.85 < URA <= 9.65
5	9.65 < URA <= 13.65
6	13.65 < URA <= 24.00
7	24.00 < URA <= 48.00
8	48.00 < URA <= 96.00
9	96.00 < URA <= 192.00
10	192.00 < URA <= 384.00
11	384.00 < URA <= 768.00
12	768.00 < URA <= 1,536.00
13	1,536 < URA <= 3,072.00
14	3,072.00 < URA <= 6,144
15	6,144 < URA (or no accuracy prediction available)

Wide Area GPS Enhancement

Wide Area GPS Enhancement (WAGE) is a feature available in Precise Positioning Service PLGR+96 receivers. The WAGE feature uses encrypted satellite data to reduce some space and control segment errors.

Each satellite broadcasts WAGE data that are valid for 6 hours after that satellite receives a data upload. These data may be used to correct satellite clock errors on other satellites that have not received an upload recently. These clock corrections are used to reduce the error caused by satellite clock biases when a period of time has passed since the last upload to those satellites. It takes approximately 12.5 minutes to download a complete WAGE data set. Only WAGE data from the most recently updated satellite are used in PLGR.

Atmospheric Errors

Atmospheric errors are those caused by the satellite RF signal passing through the earth's atmosphere. These errors include ionospheric and tropospheric delays.

Ionospheric delay affects the GPS signal as it passes through the earth's ionosphere. The ionospheric delay to GPS signals is very dynamic and depends on the time of day, the elevation angle of the satellites, and solar flare activity. Single frequency receivers use a modeled estimate of the range error induced by GPS navigation signals passing through the Earth's ionosphere. It is very difficult, however, to estimate the error in this model.

Dual frequency receivers measure this delay by tracking both the GPS L1 and L2 signals. The magnitude of the delay is frequency dependent, and the absolute delay on either frequency can be scaled from the differential delay between L1 and L2.

Tropospheric delay is the expected measure of range error induced by GPS navigation signals passing through the Earth's troposphere. This measure is based on satellite elevation. Unlike the ionospheric delay, the tropospheric delay is very predictable, and there is very little error in the compensation.

User Equipment Errors

User equipment errors are those uncertainties in the measurements that are inherent in the receiver's collection and computation of measurements. Several factors influence these uncertainties, including the GPS hardware, the design of the tracking loops, the code type being tracked (C/A or P(Y)), and the strength of the satellite signals. These uncertainties are taken into account in the Kalman filter processing done in a PLGR when computing EPE and ETE.

Multipath effects are caused by a signal arriving at the receiver site over two or more different paths. The difference between the path lengths can cause them to interfere with one another in the receiver. Buildings, parking lots, or other large objects may reflect a signal from a satellite, causing multipath effects. Signal averaging can be used to minimize the effects of multipath signals.

Error Source Summary

There are many factors that influence the accuracy of GPS measurements. Many of the factors do not contribute large errors but cumulatively are important.

In practice, the three major sources of error are (1) performing the survey when satellite geometry is poor, (2) using equipment not designed to provide the desired accuracy, and (3) mixing datums and coordinate systems.

Satellite Geometry

The most useful error measurement available is position dilution of precision (PDOP). PDOP is a number derived from the geometry of the visible satellites and changes as the satellites move in their orbits. The smaller the PDOP number, the better the satellite geometry. The PDOP value should be six, or preferably less, for accurate GPS work. Some GPS units display the PDOP or an accuracy estimate in real time. Software is available that calculates the PDOP for any planned GPS survey and should be used before conducting the survey to determine whether accurate GPS work is possible at the planned location and time. The software also can be used to determine satellite positions and whether terrain or other obstructions will affect the survey. Presurvey planning, especially relative to PDOP, can make the difference between a mediocre or failed GPS survey and a successful survey.

Equipment

Using inappropriate equipment is another major factor in GPS survey problems. The accuracy of the equipment must be known, and the equipment must be used properly. A small, inexpensive hand-held GPS unit can provide an accuracy of 10s of feet when selective availability is off and approximately 100 feet (30 m) when SA is on. A PLGR (military GPS) can provide similar accuracy when SA is on. A mapping grade GPS unit can provide 1- to 2-ft (0.5-m) accuracy if the data are post-processed and 3-ft (1-m) real-time accuracy if a satellite differential correction signal is available. Centimeter or survey-grade accuracy is possible with a local differential base station providing real-time or post-processing correction of rover data. Do not expect more accuracy than the equipment can deliver. Manufacturer estimates of accuracy are generally better than what is commonly encountered in the field.

The equipment must be well maintained. Many apparently satellite related problems are caused by equipment malfunctions, poorly charged batteries, or faulty cable connections.

Datums and Coordinate Systems

An apparent GPS problem is introduced by collecting or comparing position data based on different datums or coordinate systems. Many old topographic maps and surveys use the 1927 North American Datum (NAD27), and most new survey data are based on the 1983 North American Datum (NAD83). Also, some sites use a local reference system that is not related to a regional datum or coordinate system. Systematic errors are a good indication of a datum problem. Software is available that very accurately converts between datums and coordinate systems and is very useful for diagnosing and correcting problems. Chapter 6 of Volume 1 contains a discussion of datums, map projections, and coordinate systems.