CHAPTER 22

SATELLITE NAVIGATION

INTRODUCTION

2200. Development

The idea that led to development of the satellite navigation systems dates back to 1957 and the first launch of an artificial satellite into orbit, Russia's Sputnik I. Dr. William H. Guier and Dr. George C. Wieffenbach at the Applied Physics Laboratory of the Johns Hopkins University were monitoring the famous "beeps" transmitted by the passing satellite. They plotted the received signals at precise intervals, and noticed that a characteristic Doppler curve emerged. Since satellites generally follow fixed orbits, they reasoned that this curve could be used to describe the satellite's orbit. They then demonstrated that they could determine all of the orbital parameters for a passing satellite by Doppler observation of a single pass from a single fixed station. The Doppler shift apparent while receiving a transmission from a passing satellite proved to be an effective measuring device for establishing the satellite orbit.

Dr. Frank T. McClure, also of the Applied Physics Laboratory, reasoned in reverse: If the satellite orbit was known, Doppler shift measurements could be used to determine one's position on Earth. His studies in support of this hypothesis earned him the first National Aeronautics and Space Administration award for important contributions to space development.

In 1958, the Applied Physics Laboratory proposed exploring the possibility of an operational satellite Doppler navigation system. The Chief of Naval Operations then set forth requirements for such a system. The first successful launching of a prototype system satellite in April 1960 demonstrated the Doppler system's operational feasibility.

The **Navy Navigation Satellite System** (**NAVSAT**, also known as **TRANSIT**) was the first operational satellite navigation system. The system's accuracy was better than 0.1 nautical mile anywhere in the world, though its availability was somewhat limited. It was used primarily for the navigation of surface ships and submarines, but it also had some applications in air navigation. It was also used in hydrographic surveying and geodetic position determination.

The transit launch program ended in 1988 and the system was disestablished when the Global Positioning System became operational in 1996.

THE GLOBAL POSITIONING SYSTEM

2201. System Description

The Federal Radionavigation Plan has designated the **Navigation System using Timing And Ranging (NAVSTAR) Global Positioning System (GPS)** as the primary navigation system of the U.S. government. GPS is a spaced-based radio positioning system which provides suitably equipped users with highly accurate position, velocity, and time data. It consists of three major segments: a **space segment**, a **control segment**, and a **user segment**.

Code/Frequency	L1 (1575.42 MHz)	L2 (1227.60 MHz)	L5 (1176.45 MHz)
C/A	X		
L1C	X		
P(y)	X	X	
M-Code	X	X	
L2 CM		X	
L2 CL		X	
L5 I			X
L5Q			X

Figure 2201. GPS Satellite Code by Broadcast Frequency.

The space segment consists of 31 GPS satellites with at least 24 operational 95% of the time. Spacing of the satellites in their orbits is arranged so that at least four satellites are in view to a user at any time, anywhere on the Earth, including the North and South Poles. Each satellite transmits signals on three radio frequencies, superimposed on which are navigation and system data. Included in this data are predicted satellite ephemeris, atmospheric propagation correction data, satellite clock error information and satellite health data. The satellites orbit at an altitude of 20,200 km, in six separate orbital planes, each plane inclined 55° relative to the equator. The satellites complete an orbit approximately once every 12 hours.

GPS satellites transmit **pseudorandom noise (PRN)** sequence-modulated radio frequencies, designated L1 (1575.42 MHz), L2 (1227.60 MHz) and L5 (1176.45 MHz). Various transmissions are sent on these channels as shown in Table 2201.

Superimposed on both the legacy C/A and P(y) codes is the navigation message. This message contains the satellite ephemeris data, atmospheric propagation correction data, and satellite clock bias. In addition, four additional new messages have been introduced by the so called GPS modernization: L2-CNAV, CNAV-2, L5-CNAV and MNAV. The "legacy" message and the first three of the modernized GPS are civil messages, while the MNAV is a military message. In modernized GPS, the same type of contents as the legacy navigation message (NAV) is transmitted but at a higher rate and with improved robustness.

The messages L2-CNAV, L5-CNAV and MNAV have a similar structure and (modernized) data format. The new format allows more flexibility, better control and improved content. Furthermore, the MNAV includes new improvements for the security and robustness of the military message. The CNAV-2 is modulated onto L1CD, sharing the same band as the "legacy" navigation message.

GPS assigns a unique C/A code and a unique P code to each satellite. This practice, known as **code division multiple access (CDMA)**, allows all satellites the use of a common carrier frequency while still allowing the receiver to determine which satellite is transmitting. CDMA also allows for easy user identification of each GPS satellite. Since each satellite broadcasts using its own unique C/A and P code combination, it can be assigned a unique **PRN sequence number**. This number is how a satellite is identified when the GPS control system communicates with users about a particular GPS satellite.

The control segment includes a **master control station** (MCS), a number of monitor stations, and ground antennas located throughout the world. The master control station, located in Colorado Springs, Colorado, consists of equipment and facilities required for satellite monitoring, telemetry, tracking, commanding, control, uploading, and navigation message generation. The monitor stations, located in Hawaii, Colorado Springs, Kwajalein, Diego Garcia, and Ascension Island, passively track the satellites, accumulating ranging data from the satellites' signals and relaying them to the MCS. The MCS processes this information to determine satellite position and signal data accuracy, updates the navigation message of each satellite and relays this information to the ground antennas. The ground antennas then transmit this information to the satellites. The ground antennas, located at Ascension Island, Diego Garcia, and Kwajalein, are also used for transmitting and receiving satellite control information.

The user equipment is designed to receive and process signals from four or more orbiting satellites either simultaneously or sequentially. The processor in the receiver then converts these signals to navigation information. Since GPS is used in a wide variety of applications, from marine navigation to land surveying, these receivers can vary greatly in function and design.

2202. System Capabilities

GPS provides multiple users with accurate, continuous, worldwide, all-weather, common-grid, three-dimensional positioning and navigation information.

To obtain a navigation solution of position (latitude, longitude, and altitude) and time (four unknowns), four satellites must be used. The GPS user measures pseudorange and pseudorange rate by synchronizing and tracking the navigation signal from each of the four selected satellites. Pseudorange is the true distance between the satellite and the user plus an offset due to the user's clock bias. Pseudorange rate is the true slant range rate plus an offset due to the frequency error of the user's clock. By decoding the ephemeris data and system timing information on each satellite's signal, the user's receiver/processor can convert the pseudorange and pseudorange rate to three-dimensional position and velocity. Four measurements are necessary to solve for the three unknown components of position (or velocity) and the unknown user time (or frequency) bias.

The navigation accuracy that can be achieved by any user depends primarily on the variability of the errors in making pseudorange measurements, the instantaneous geometry of the satellites as seen from the user's location on Earth, and the presence of **Selective Availability (SA)**. Selective Availability is discussed further below.

2203. Global Positioning System Concepts

GPS receivers (or user equipment) measure distances between satellites in orbit and a receiver on Earth, and computes spheres of position from those distances. The intersections of those spheres of position then determine the receiver's position.

The distance measurements described above are done by comparing timing signals generated simultaneously by the satellites' and receiver's internal clocks. These signals, characterized by a special wave form known as the pseudo-random code, are generated in phase with each other. The signal from the satellite arrives at the receiver following a time delay proportional to its distance traveled. This time delay is detected by the phase shift between the received pseudo-random code and the code generated by the receiver. Knowing the time required for the signal to reach the receiver from the satellite allows the receiver to calculate the distance from the satellite. The receiver, therefore, must be located on a sphere centered at the satellite with a radius equal to this distance measurement. The intersection of three spheres of position yields two possible points of receiver position. One of these points can be disregarded since it is hundreds of miles from the surface of the Earth. Theoretically, then, only three time measurements are required to obtain a fix from GPS.

In practice, however, a fourth measurement is required to obtain an accurate position from GPS. This is due to receiver clock error. Timing signals travel from the satellite to the receiver at the speed of light; even extremely slight timing errors between the clocks on the satellite and in the receiver will lead to tremendous range errors. The satellite's atomic clock is accurate to 10^{-9} seconds; installing a clock that accurate on a receiver would make the receiver prohibitively expensive. Therefore, receiver clock accuracy is sacrificed, and an additional satellite timing measurement is made. The fix error caused by the inaccuracies in the receiver clock is reduced by simultaneously subtracting a constant timing error from four satellite timing measurements until a pinpoint fix is reached.

Assuming that the satellite clocks are perfectly synchronized and the receiver clock's error is constant, the subtraction of that constant error from the resulting distance determinations will reduce the fix error until a "pinpoint" position is obtained. It is important to note here that the number of lines of position required to employ this technique is a function of the number of lines of position required to obtain a fix. GPS determines position in three dimensions; the presence of receiver clock error adds an additional unknown. Therefore, four timing measurements are required to solve for the resulting four unknowns.

2204. GPS Signal Coding

The GPS L1 band (1575.42 MHz) has turned out to be the most important band for navigation purposes. Indeed most of the applications in the world today are based on the signals transmitted at this frequency. Three signals are transmitted at the moment by GPS in L1: C/A Code, P(Y) Code and M-Code. In the future, an additional new civil signal, known as L1C, will also be transmitted.

GPS is transmitting in the L2 band (1227.60 MHz). It is modernized civil signal known as L2C together with the P(Y) Code and the M-Code. The P(Y) Code and M-Code were already described shortly in the previous chapter and the properties and parameters are thus similar to those in the L1 band. In addition, for Block IIR-M, IIF, and subsequent blocks of SVs, two additional PRN ranging codes will be transmitted. They are the L2 Civil Moderate (L2 CM) code and the L2 Civil Long (L2 CL) code. These two signals are time multiplexed so that the resulting chipping rate is double as high as that of each individual signal.

The GPS L5 (1176.45 MHz) signal will be transmitted for the first time on board IIF satellites. The GPS carriers of the L5 band are modulated by two bit trains in phase quadrature: the L5 data channel and the L5 pilot channel. Moreover, two PRN ranging codes are transmitted on L5.

For a more detailed analysis of GPS signal coding see Appendix C in Volume I.

2205. The Correlation Process

The correlation process compares the signal received from the satellites with the signal generated by the receiver by comparing the square wave function of the received signal with the square wave function generated by the receiver. The computer logic of the receiver recognizes the square wave signals as either a +1 or a 0 depending on whether the signal is "on" or "off." The signals are processed and matched by using an **autocorrelation function**.

This process defines the necessity for a "pseudo-random code." The code must be repeatable (i.e., non-random) because it is in comparing the two signals that the receiver makes its distance calculations. At the same time, the code must be random for the correlation process to work; the randomness of the signals must be such that the matching process excludes all possible combinations except the combination that occurs when the generated signal is shifted a distance proportional to the received signal's time delay. These simultaneous requirements to be both repeatable (non-random) and random give rise to the description of "pseudo-random"; the signal has enough repeatability to enable the receiver to make the required measurement while simultaneously retaining enough randomness to ensure incorrect calculations are excluded.

2206. Precise Positioning Service and Standard Positioning Service

Two levels of navigational accuracy are provided by the GPS: the **Precise Positioning Service (PPS)** and the **Standard Positioning Service (SPS)**. GPS was designed, first and foremost, by the U.S. Department of Defense as a United States military asset; its extremely accurate positioning capability is an asset access to which the U.S. military may need to limit during time of war to prevent use by enemies. Therefore, the PPS is available only to authorized users, mainly the U.S. military and authorized allies. SPS, on the other hand, is available worldwide to anyone possessing a GPS receiver. The accuracy of the GPS signal in space is actually the same for both the civilian GPS service and the military GPS service.

However, SPS broadcasts on one frequency, while PPS uses two. This means military users can perform ionospheric correction, a technique that reduces radio degradation caused by the Earth's atmosphere. With less degradation, PPS provides better accuracy than the basic SPS.

The ongoing GPS modernization program is adding new civilian signals and frequencies to the GPS satellites, enabling ionospheric correction for all users. Eventually, the accuracy difference between military and civilian GPS will disappear. But military GPS will continue to provide important advantages in terms of enhanced security and jam resistance.

Anti-spoofing (A-S) is designed to negate any hostile imitation of GPS signals. The technique alters the P code into another code, designated the Y code. The C/A code remains unaffected. The U.S. employs this technique to the satellite signals at random times and without warning; therefore, civilian users are unaware when this P code transformation takes place. Since anti-spoofing is applied only to the P code, the C/A code is not protected and can be spoofed.

GPS PPS receivers can use either the P code or the C/A code, or both, in determining position. Maximum accuracy is obtained by using the P code on both L1 and L2. The difference in propagation delay is then used to calculate ionospheric corrections. The C/A code is normally used to acquire the satellite signal and determine the approximate P code phase. Some PPS receivers possess a clock accurate enough to track and lock on the P code signal without initially tracking the C/A code. Some PPS receivers can track only the C/A code and disregard the P code entirely. Since the C/A code is transmitted on only one frequency, the dual frequency ionosphere correction methodology is unavailable and an ionospheric modeling procedure is required to calculate the required corrections.

SPS receivers, as mentioned above, provide positions with a degraded accuracy. The A-S feature denies SPS users access to the P code when transformed to the Y code. Therefore, the SPS user cannot rely on access to the P code to measure propagation delays between L1 and L2 and compute ionospheric delay corrections. Consequently, the typical SPS receiver uses only the C/A code because it is unaffected by A-S. Like PPS, the C/A is transmitted only on L1, the dual frequency method of calculating ionospheric corrections is unavailable; an ionospheric modeling technique must be used. This is less accurate than the dual frequency method; this degradation in accuracy is accounted for in the 100-meter accuracy calculation.

2207. Selective Availability Discontinued

In May 2000, President Bill Clinton directed the Department of Defense to turn off the GPS **Selective Availability (SA)** feature. In 2007, the U.S. government announced plans to permanently eliminate SA by building the GPS III satellites without it. SA was a method to degrade GPS accuracy to civilian users.

2208. GPS Receiver Operations

In order for the GPS receiver to navigate, it has to track satellite signals, make pseudorange measurements, and collect navigation data.

A typical satellite tracking sequence begins with the receiver determining which satellites are available for it to track. Satellite visibility is determined by user-entered predictions of position, velocity, and time, and by almanac information stored internal to the receiver. If no stored almanac information exists, then the receiver must attempt to locate and lock onto the signal from any satellite in view. When the receiver is locked onto a satellite, it can demodulate the navigation message and read the almanac information about all the other satellites in the constellation. A carrier tracking loop tracks the carrier frequency while a code tracking loop tracks the C/A and P code signals. The two tracking loops operate together in an iterative process to acquire and track satellite signals.

The receiver's carrier tracking loop will locally generate an L1 carrier frequency which differs from the satellite produced L1 frequency due to a Doppler shift in the received frequency. This Doppler offset is proportional to the relative velocity along the line of sight between the satellite and the receiver, subject to a receiver frequency bias. The carrier tracking loop adjusts the frequency of the receiver-generated frequency until it matches the incoming frequency. This determines the relative velocity between the satellite and the receiver. The GPS receiver uses this relative velocity to calculate the velocity of the receiver. This velocity is then used to aid the code tracking loop.

The code tracking loop is used to make pseudorange measurements between the GPS receiver and the satellites. The receiver's tracking loop will generate a replica of the targeted satellite's C/A code with estimated ranging delay. In order to match the received signal with the internally generated replica, two things must be done: 1) the center frequency of the replica must be adjusted to be the same as the center frequency of the received signal; and 2) the phase of the replica code must be lined up with the phase of the received code. The center frequency of the replica is set by using the Doppler-estimated output of the carrier tracking loop. The receiver will then slew the code loop generated C/A code though a millisecond search window to correlate with the received C/A code and obtain C/A tracking.

Once the carrier tracking loop and the code tracking loop have locked onto the received signal and the C/A code has been stripped from the carrier, the navigation message is demodulated and read. This gives the receiver other information crucial to a pseudorange measurement. The navigation message also gives the receiver the handover word, the code that allows a GPS receiver to shift from C/A code tracking to P code tracking.

The handover word is required due to the long phase (seven days) of the P code signal. The C/A code repeats every millisecond, allowing for a relatively small search window. The seven day repeat period of the P code requires that the receiver be given the approximate P code phase to narrow its search window to a manageable time. The handover word provides this P code phase information. The handover word is repeated every subframe in a 30 bit long block of data in the navigation message. It is repeated in the second 30 second data block of each subframe. For some receivers, this handover word is unnecessary; they can acquire the P code directly. This normally requires the receiver to have a clock whose accuracy approaches that of an atomic clock. Since this greatly increases the cost of the receiver, most receivers for non-military marine use do not have this capability.

Once the receiver has acquired the satellite signals from four GPS satellites, achieved carrier and code tracking, and has read the navigation message, the receiver is ready to begin making pseudorange measurements. Recall that these measurements are termed *pseudorange* because a receiver clock offset makes them inaccurate; that is, they do not represent the true range from the satellite, only a range biased by a receiver clock error. This clock bias introduces a fourth unknown into the system of equations for which the GPS receiver must solve (the other three being the x coordinate, y coordinate, and z coordinate of the receiver position). The receiver solves this clock bias problem by making a fourth pseudorange measurement, resulting in a fourth equation to allow solving for the fourth unknown. Once the four equations are solved, the receiver has an estimate of the receiver's position in three dimensions and of GPS time. The receiver then converts this position into coordinates referenced to an Earth model based on the World Geodetic System (1984).

2209. User Range Errors and Geometric Dilution of Precision

There are two formal position accuracy requirements for GPS:

1) The PPS spherical position accuracy shall be 16 meters SEP (spherical error probable) or better.

2) The SPS user two dimensional position accuracy shall be 100 meters 2 DRMS (distance root mean squared) or better.

Assume that a universal set of GPS pseudorange measurements results in a set of GPS position measurements. The accuracy of these measurements will conform to a normal (i.e. values symmetrically distributed around a mean of zero) probability function because the two most important factors affecting accuracy, the **geometric dilution of precision (GDOP)** and the **user equivalent range error (UERE)**, are continuously variable.

The UERE is the error in the measurement of the pseudoranges from each satellite to the user. The UERE is the product of several factors, including the clock stability, the predictability of the satellite's orbit, errors in the 50 Hz navigation message, the precision of the receiver's correlation process, errors due to atmospheric distortion and the calculations to compensate for it, and the quality of the satellite's signal. The UERE, therefore, is a random error which is the function of errors in both the satellites and the user's receiver.

The GDOP depends on the geometry of the satellites in relation to the user's receiver. It is independent of the quality of the broadcast signals and the user's receiver. Generally speaking, the GDOP measures the "spread" of the satellites around the receiver. The optimum case would be to have one satellite directly overhead and the other three spaced 120° around the receiver on the horizon. The worst GDOP would occur if the satellites were spaced closely together or in a line overhead.

There are special types of DOP's (dilution of precision) for each of the position and time solution dimensions; these particular DOP's combine to determine the GDOP. For the vertical dimension, the **vertical dilution of precision (VDOP)** describes the effect of satellite geometry on altitude calculations. The **horizontal dilution of precision (HDOP)** describes satellite geometry's effect on position (latitude and longitude) errors. These two DOP's combine to determine the **position dilution of precision (PDOP)**. The PDOP combined with the **time dilution of precision (TDOP)** results in the GDOP. See Figure 2209.

2210. Ionospheric Delay Errors

Section 2209 covered errors in GPS positions due to errors inherent in the satellite signal (UERE) and the geometry of the satellite constellation (GDOP). Another major cause of accuracy degradation is the effect of the ionosphere on the radio frequency signals that comprise the GPS signal.

A discussion of a model of the Earth's atmosphere will be useful in understanding this concept. Consider the Earth as surrounded by three layers of atmosphere. The first layer, extending from the surface of the Earth to an altitude of approximately 10 km, is known as the **troposphere**. Above the troposphere and extending to an altitude of approximately 50 km is the **stratosphere**. Finally, above the stratosphere and extending to an altitude that varies as a function of the time of day is the **ionosphere**. Though radio signals are subjected to effects which degrade its accuracy in all three layers of this atmospheric model, the effects of the ionosphere are the most significant to GPS operation.

The ionosphere, as the name implies, is that region of the atmosphere which contains a large number of ionized molecules and a correspondingly high number of free electrons. These charged molecules have lost one or more electrons. No atom will lose an electron without an input of

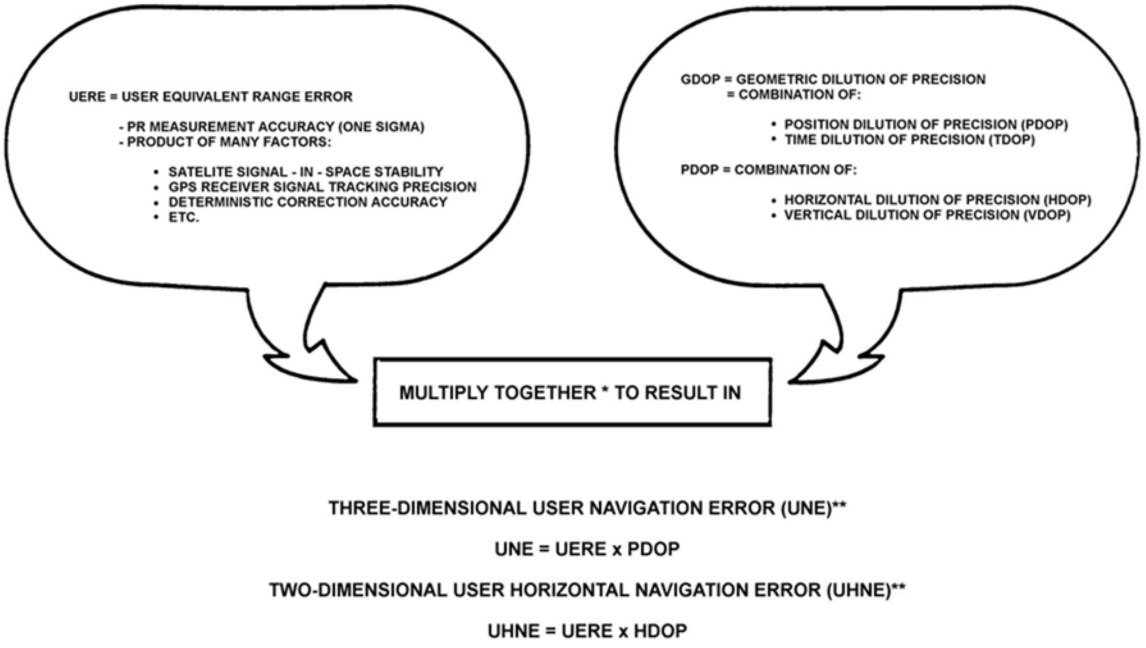

Figure 2209. Position and time error computations.

energy; the energy input that causes the ions to be formed in the ionosphere comes from the **ultraviolet (U-V)** radiation of the Sun. Therefore, the more intense the Sun's rays, the larger the number of free electrons which will exist in this region of the atmosphere.

The largest effect that this ionospheric effect has on GPS accuracy is a phenomenon known as **group time delay**. As the name implies, group time delay results in a delay in the time a signal takes to travel through a given distance. Obviously, since GPS relies on extremely accurate timing measurement of these signals between satellites and ground receivers, this group time delay can have a noticeable effect on the magnitude of GPS position error.

The group time delay is a function of several elements. It is inversely proportional to the square of the frequency at which the satellite transmits, and it is directly proportional to the atmosphere's **total electron content (TEC)**, a measure of the degree of the atmosphere's ionization. The general form of the equation describing the delay effect is:

$$\Delta t = \frac{(K \quad TEC)}{f^2}$$

where

Δt = group time delay
f = operating frequency
K = constant

Since the Sun's U-V radiation ionizes the molecules in the upper atmosphere, it stands to reason that the time delay value will be highest when the Sun is shining and lowest at night. Experimental evidence has borne this out, showing that the value for TEC is highest around 1500 local time and lowest around 0500 local time. Therefore, the magnitude of the accuracy degradation caused by this effect will be highest during daylight operations. In addition to these daily variations, the magnitude of this time delay error also varies with the seasons; it is highest at the vernal equinox. Finally, this effect shows a solar cycle dependence. The greater the number of sunspots, the higher the TEC value and the greater the group time delay effect. The solar cycle typically follows an eleven year pattern. The current solar cycle began on January 4, 2008 with minimal activity until early 2010. The cycle is on track to have the lowest recorded sunspot activity since cycle 14 which reached maximum in 1906. See Figure 2210 Solar cycle 24 prediction.

Given that this ionospheric delay introduces a serious accuracy degradation into the system, how does GPS account for it? There are two methods used: (1) the dual frequency technique, and (2) the ionospheric delay method.

2211. Dual Frequency Correction Technique

As the term implies, the dual frequency technique requires the ability to acquire and track both the L1 and L2 frequency signals. Recall from the discussion in Section 2204 that the C/A and P codes are transmitted on carrier frequency L1, but only the P code is transmitted on L2. Recall also that only authorized operators with access to DOD cryptographic material are able to copy the P code. It follows, then, that only those authorized users are able to copy the L2 carrier frequency. Therefore, only those authorized users are able to use the dual frequency correction method. The dual frequency method measures the distance between the satellite and the user based on both the L1 and L2 carrier signal. These ranges will be different because the group time delay for each signal will

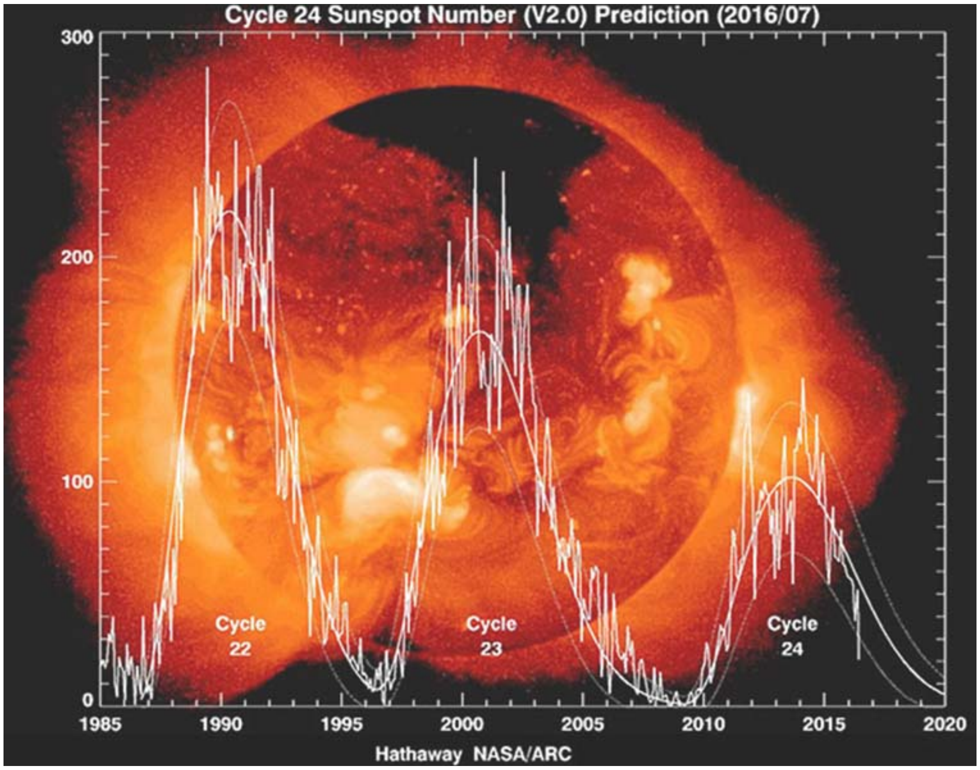

Figure 2210. Solar cycle prediction. Courtesy of NASA.

be different. This is because of the frequency dependence of the time delay error. The range from the satellite to the user will be the true range combined with the range error caused by the time delay, as shown by the following equation:

$$R(f) = R_{actual} + \text{error term}$$

where R(f) is the range which differs from the actual range as a function of the carrier frequency. The dual frequency correction method takes two such range measurements, R(L1) and R(L2). Recall that the error term is a function of a constant divided by the square of the frequency. By combining the two range equations derived from the two frequency measurements, the constant term can be eliminated and one is left with an equation in which the true range is simply a function of the two carrier frequencies and the measured ranges R(L1) and R(L2). This method has two major advantages over the ionospheric model method: (1) it calculates corrections from real-time measured data, therefore, it is more accurate; (2) it alleviates the need to include ionospheric data on the navigation message. A significant portion of the data message is devoted to ionospheric correction data. If the receiver is dual frequency capable, then it does not need any of this data.

The vast majority of maritime users cannot copy dual frequency signals. For them, the ionospheric delay model provides the correction for the group time delay.

2212. The Ionospheric Delay Model

The ionospheric delay model mathematically models the diurnal ionospheric variation. The value for this time delay is determined from a cosinusoidal function into which coefficients representing the maximum value of the time delay (i.e., the amplitude of the cosine wave representing the delay function), the time of day, the period of the variation and a minimum value of delay are introduced. This model is designed to be most accurate at the diurnal maximum. This is obviously a reasonable design consideration because it is at the time of day when the maximum diurnal time delay occurs that the largest magnitude of error appears. The coefficients for use in this delay model are transmitted to the receiver in the navigation data message. As stated in Section 2211, this method of correction is not as accurate as the dual frequency method; however, for the non-military user, it is the only method of correction available.

2213. Multipath Reflection Errors

Multipath reflection errors occur when the receiver detects parts of the same signal at two different times. The first reception is the direct path reception, the signal that is received directly from the satellite. The second reception is from a reflection of that same signal from the ground or any other reflective surface. The direct path signal arrives first, the reflected signal, having had to travel a longer distance to the receiver, arrives later. The GPS signal is designed to minimize this multipath error. The L1 and L2 frequencies used demonstrate a diffuse reflection pattern, lowering the signal strength of any reflection that arrives at the receiver. In addition, the receiver's antenna can be designed to reject a signal that it recognizes as a reflection. In addition to the properties of the carrier frequencies, the high data frequency of both the P and C/A codes and their resulting good correlation properties minimize the effect of multipath propagation.

The design features mentioned above combine to reduce the maximum error expected from multipath propagation to less than 20 feet.

DIFFERENTIAL GPS

2214. Differential GPS Concept

The discussions above make it clear that the Global Positioning System provides the most accurate positions available to navigators today. They should also make clear that the most accurate positioning information is available to only a small fraction of the using population: U.S. and allied military. For most open ocean navigation applications, the degraded accuracy inherent in selective availability and the inability to copy the precision code presents no serious hazard to navigation. A mariner seldom if ever needs greater than 100 meter accuracy in the middle of the ocean.

It is a different situation as the mariner approaches shore. Typically for harbor approaches and piloting, the mariner will shift to visual piloting. The increase in accuracy provided by this navigational method is required to ensure ship's safety. The 100 meter accuracy of GPS in this situation is not sufficient. Any mariner who has groped his way through a restricted channel in a thick fog will certainly appreciate the fact that even a degraded GPS position is available for them to plot. However, 100 meter accuracy is not sufficient to ensure ship's safety in most piloting situations. In this situation, the mariner needs P code accuracy. The problem then becomes how to obtain the accuracy of the Precise Positioning Service with due regard to the legitimate security concerns of the U.S. military. The answer to this seeming dilemma lies in the concept of **Differential GPS (DGPS)**.

Differential GPS is a system in which a receiver at an accurately surveyed position utilizes GPS signals to calculate timing errors and then broadcasts a correction signal to account for these errors. This is an extremely powerful concept. The errors which contribute to GPS accuracy degradation, ionospheric time delay and selective availability, are experienced simultaneously by both the DGPS receiver and a relatively close user's receiver. The extremely high altitude of the GPS satellites means that, as long as the DGPS receiver is within 100-200 km of the user's receiver, the user's receiver is close enough to take advantage of any DGPS correction signal.

The theory behind a DGPS system is straightforward. Located on an accurately surveyed site, the DGPS receiver already knows its location. It receives data which tell it where the satellite is. Knowing the two locations, it then calculates the theoretical time it should take for a satellite's signal to reach it. It then compares the time that it actually takes for the signal to arrive. This difference in time between the theoretical and the actual is the basis for the DGPS receiver's computation of a timing error signal; this difference in time is caused by all the errors to which the GPS signal is subjected; errors, except for receiver error and multipath error, to which both the DGPS and the user's receivers are simultaneously subject. The DGPS system then broadcasts a timing correction signal, the effect of which is to correct for selective availability, ionospheric delay, and all the other error sources the two receivers share in common.

For suitably equipped users, DGPS results in positions at least as accurate as those obtainable by the Precise Positioning Service. This capability is not limited to simply displaying the correct position for the navigator to plot. The DGPS position can be used as the primary input to an electronic chart system, providing an electronic readout of position accurate enough to pilot safely in the most restricted channel.

SATELLITE BASED AUGMENTATION SYSTEMS (SBAS)

2215. WAAS/LAAS for Aeronautical Use

The **Wide Area Augmentation System (WAAS)** program, which corrects for GPS signal errors caused by ionospheric disturbances, timing, and satellite orbit errors, provides vital integrity information regarding the health of each GPS satellite. The concept is similar to the DGPS concept, except that correctional signals are sent from geostationary satellites via HF signals directly to the user's GPS receiver. This eliminates the need for a separate receiver and antenna, as is the case with DGPS. WAAS is intended for en route air navigation, with 25 reference stations widely spaced across the United States that monitor GPS satellite data and two master stations on either coast, and creates a GPS correction message. WAAS provides coverage of the entire U.S. and parts of Mexico and Canada.

The **Local Area Augmentation System (LAAS)** is intended for precision airport approaches, with reference stations located at airports and broadcasting their correction message on VHF radio frequencies.

While many marine GPS receivers incorporate WAAS circuitry (but not the more accurate, shorter-range LAAS), WAAS is not optimized for surface navigation because the HF radio signals are line-of-sight and are transmitted from geostationary satellites. At low angles to the horizon, the WAAS signal may be blocked and the resulting GPS position accuracy significantly degraded with no warning. The DGPS signal, on the other hand, is a terrain-following signal that is unaffected by objects in its path. It simply flows around them and continues on unblocked.

The accuracy of WAAS and DGPS is comparable, on the order of a few meters. Any GPS receiver equipped to receive WAAS has its accuracy improved to less than 3 meters. Both systems have been found in actual use to provide accuracies somewhat better than designed. DGPS was designed to provide 10 meter accuracy 95% of the time, but in actual use one can expect about 1-3 meter accuracy when the user is within 100 miles of the DGPS transmitter. Over 100 miles, DGPS accuracy will commonly degrade by an additional 1 meter per 100 miles from the transmitter site.

The WAAS signal, while not certified for use in the marine environment as is DGPS, can be a very useful navigational tool if its limitations are understood. In open waters of the continental U.S., the WAAS signal can be expected to be available and useful, provided the receiver has WAAS circuitry and is programmed to use the WAAS data. Outside the U.S., or in any area where tall buildings, trees, or other obstructions rise above the horizon, the WAAS signal may be blocked, and the resulting GPS fix could be in error by many meters. Since the highest accuracy is necessary in the most confined waters, WAAS should be used with extreme caution in these areas.

WAAS can enhance the navigator's situational awareness when available, but availability is not assured. Further, a marine receiver will provide no indication when WAAS data is not a part of the fix. [Aircraft GPS receivers may contain Receiver Autonomous Integrity Monitoring (RAIM) software, which provides warning of WAAS satellite signal failure, and removes the affected signal from the fix solution.]

LAAS data, broadcast on VHF, is less subject to blocking, but is only available in selected areas near airports. Its range is about 30 miles. It is therefore not suitable for general marine navigational use.

2216. More Information

For more information on the Global Positioning System (GPS) and related topics see the link provided in Figure 2216.

Figure 2216. GPS.gov at http://www.gps.gov

2217. Foreign SBAS

SBAS systems are spreading out all over the world. More and more, it is believed that upon dual-frequency SBAS service provision, a seamless navigation will be possible from and to any two locations in the world.

Presently, three foreign SBAS systems are operational. These are Japan's Multi-functional Transport Satellite based Augmentation System (MSAS), the European Geostationary Navigation Overlay Service (EGNOS) and India's GPS and Geo-Augmented Navigation System (GAGAN),

Other foreign SBAS are under implementation such as SDCM (System of Differential Correction and Monitoring) in Russia and SNAS (Satellite Navigation Augmentation System) in China. Still others are under development or feasibility studies; SACCSA (Solucion de Aumentacion para Caribe, Centro y Sudamerica) would cover Central & South America including the Caribbean. Member States to SACCSA include Argentina Bolivia, Colombia, Costa Rica, Guatemala, Panama, Spain and Venezuela. Malaysia, much of Africa and South Korean SBAS are also studying SBAS particularly for aeronautical navigation.

NON-U.S. SATELLITE NAVIGATION SYSTEMS

2218. The Galileo System

Galileo is the **global navigation satellite system** (GNSS) that is currently being created by the European Union (EU) through the European Space Agency (ESA) and the European GNSS Agency (GSA), with two ground operations centers in Germany and Italy.

One of the aims of Galileo is to provide an indigenous alternative high-precision positioning system upon which European nations can rely, independently from other country systems, in case they were disabled by their operators.

The use of basic (low-precision) Galileo services will be free and open to everyone. The high-precision capabilities will be available for paying commercial users. Galileo is intended to provide horizontal and vertical position measurements within one meter precision, and better positioning services at high latitudes than other positioning systems.

Galileo is to provide a new global search and rescue (SAR) function as part of the Medium-altitude Earth Orbit Search and Rescue (MEOSAR) system. Satellites will be equipped with a transponder which will relay distress signals from emergency beacons to a rescue coordination center, which will then initiate a rescue operation. At the same time, the system is projected to provide a signal, the Return Link Message (RLM), to the emergency beacon, informing victims that their situation has been detected and help is on the way. This latter feature is new and is considered a major upgrade compared to the existing international search and rescue system (Cospas-Sarsat), which does not provide feedback to the user.

Galileo will also provide an important feature for civilian use that GPS does not: integrity monitoring. Currently, a civilian GPS user receives no indication that his unit is not receiving proper satellite signals, there being no provision for such notification in the code. However, Galileo will provide such a signal, alerting the user that the system is operating improperly.

The first Galileo test satellite, the GIOVE-A, was launched 28 December 2005, while the first satellite to be part of the operational system was launched on 21 October 2011. As of May 2016 the system has 14 of 30 satellites in orbit. Galileo will start offering Early Operational Capability (EOC) from 2016, go to Initial Operational Capability (IOC) in 2017-18 and reach Full Operational Capability (FOC) in 2019. The complete 30-satellite Galileo system (24 operational and 6 active spares) is expected by 2020.

For detailed information on the Galileo signal structure see Appendix C in Volume I.

2219. GLONASS

The **Global Navigation Satellite System (GLONASS)**, under the control of the Russian military, has been in use since 1993, and is based on the same principles as GPS. The space segment consists of 24 satellites in three orbital planes, the planes separated by 120 degrees and the individual satellites by 45 degrees. The orbits are inclined to the equator at an angle of 64.8 degrees, and the orbital period is about 11hours, 15minutes at an altitude of 19,100 km (10,313 nm). The designed system fix accuracy for civilian use is 100 meters horizontal (95%), 150 meters vertical, and 15 cm/sec. in velocity. Military codes provide accuracies of some 10-20 meters horizontal.

The ground segment of GLONASS lies entirely within the former Soviet Union. Reliability has been an ongoing problem for the GLONASS system, but new satellite designs with longer life spans are addressing these concerns. The user segment consists of various types of receivers that provide position, time, and velocity information.

GLONASS signals are in the L-band, operating in 25 channels with 0.5625 MHz separation in 2 bands: from 1602.5625 MHz to 1615.5 MHz, and from 1240 to 1260 MHz.

For detailed information on the GLONASS signal structure see Appendix C in Volume I.

2220. BeiDou

The **BeiDou Navigation Satellite System (BDS)**, also known as BeiDou-2, is China's second-generation satellite navigation system that will be capable of providing positioning, navigation, and timing services to users on a continuous worldwide basis.

Although the evolution of its regional navigation system towards a global solution started in 1997, the formal approval by the Government of the development and deployment of BDS System was done in 2006 and it is expected to provide global navigation services by 2020, similarly to the GPS, GLONASS or Galileo systems.

As of December 2011, the BeiDou system was officially announced to provide Initial Operational Service providing initial passive positioning navigation and timing services for the whole Asia-Pacific region with a constellation of 10 satellites (5 GEO satellites and 5 Inclined Geosynchronous Satellite Orbit (IGSO) satellites). During 2012, 5 additional satellites (1 GEO satellite and 4 Medium-Earth Orbit (MEO) satellites) were launched increasing to 14 the number of satellites of the constellation. In 2020, the system is going to launch the remaining satellites and evolve towards global navigation capability.

The BeiDou Space Segment consists of a constellation of 35 satellites, which include 5 geostationary earth orbit (GEO) satellites and 30 non-GSO satellites. The system is currently under development evolving from a regional system called BeiDou-1, and in the first phase will provide global navigation services by 2020, similarly to the GPS, GLONASS or Galileo systems.

For detailed information on the BeiDou signal plan see Appendix C in Volume I.

2221. IRNSS

The **Indian Regional Navigational Satellite System (IRNSS)** is a regional satellite navigation system owned by the Indian government. The system is being developed by Indian Space Research Organization (ISRO).

In April 2016, with the last launch of the constellation's satellite, IRNSS was renamed Navigation Indian Constellation (NAVIC) by India's Prime Minister Narendra Modi.

IRNSS will be an independent and autonomous regional navigation system aiming a service area of about 1500 kilometers around India. The system will be under complete Indian control, with the space segment, ground segment and user receivers all being built in India. It will have a range of applications including personal navigation.

For detailed information on the IRNSS signal plan see Appendix C in Volume I.

2222. QZSS

The **Quasi-Zenith Satellite System (QZSS)** is a regional navigation satellite system commissioned by the Japanese Government as a National Space Development Program.

QZSS was authorized by the Japanese government in 2002. At the beginning the system was developed by the Advanced Space Business Corporation (ASBC) team, including Mitsubishi Electric Corp., Hitachi Ltd., and GNSS Technologies Inc. When in 2007 ASBC collapsed, the work was taken over by JAXA together with Satellite Positioning Research and Application Center (SPAC), established in February 2007 and approved by the Ministers associated with QZSS research and development.

The QZSS service area covers East Asia and Oceania region and its platform is multi-constellation GNSS. The QZSS system is not required to work in a stand-alone mode, but together with data from other GNSS satellites.

For detailed information on the QZSS signal plan see Appendix C in Volume I.

2223. References

Ávila Rodríguez, José Ángel. (2008). *On Generalized Signal Waveforms for Satellite Navigation*. University FAF, Munich. Retrieved from: https://athene-forschung.unibw.de/doc/86167/86167.pdf