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CHAPTER 4
GLOBAL POSITIONING SYSTEM

The NAVSTAR (**NAV**igation **S**atellite **T**iming **A**nd **R**anging) GPS (**G**lobal **P**ositioning **S**ystem) is a space-based navigation and timing system operated and maintained by the Department of Defense. It continuously provides accurate, all-weather, 3-dimensional (3D) position, velocity and time over the entire world. To make full use of the user equipment available for this system, a general knowledge of GPS operational theory is necessary.

Section I
CONFIGURATION, SIGNALS, AND CODE

4-1 System Configuration. The NAVSTAR GPS is configured into three distinct segments; each one very much dependent upon the other. (See Figure 4-1.)

a. Space Segment. Originally, the complete Space Segment was to consist of 24 Block II satellites (Block I satellites were considered developmental, Block IIR (Replacement) satellites are being developed to provide system operations through the year 2025). Currently, more than 24 satellites are in orbit. The satellites are arranged into six orbital planes, each inclined 55° from the equator. Each orbital plane contains at least four unevenly spaced satellites orbiting the Earth twice a day at an altitude of 10,898 miles. The satellites move continuously through their orbit in the same direction as the Earth's rotation. They orbit the earth twice in 23h 56m 04.091s solar time or one 24 hour sidereal day.

b. Control Segment. The Control Segment consists of five unmanned monitor/tracking stations located in Hawaii, Colorado, Ascension Island, Diego Garcia, and Kwajalein. The tracking stations use special receivers to track each satellite individually. The information obtained from tracking the satellites is used in

Figure 4-1 System Configuration; Space, Control, and User Segments.

controlling the satellites and predicting their orbits. Three of the stations (Ascension Island, Diego Garcia, and Kwajalein) are used for transmitting information back to the satellites. All data collected at the tracking stations is transmitted to the Master Control Center, located at Colorado Springs, Colorado, where it is processed and analyzed. Ephemerides, clock corrections, and other message data are then transmitted back to the three stations for subsequent transmittal back to the satellites. The Master Control Center is also responsible for the daily management and control of the satellites and the overall Control Segment.

c. User Segment. The User Segment consists of any one with a GPS receiver. Both military and civilian personnel, including the enemy, use these receivers. Methods used by DoD to deny the enemy of high accuracy or even to deny him use of the GPS signals are discussed later in this section.

4-2 Satellite Signals

a. Carrier Frequencies. Each GPS satellite broadcasts signals on two spread-spectrum radio frequencies (RF). These are termed carrier frequencies because they are modulated with signal codes "carried" on the radio wave. The satellite's onboard atomic clocks generate a fundamental frequency of 10.23 megahertz (MHz) (10,230,000 cycles per second), which is multiplied by a factor, which produces the actual carrier frequency. (See Figure 4-5.)

1. **L1-RF.** Multiplying the fundamental frequency by 154 generates the Link 1 RF (L1) carrier frequency. It is centered at 1575.42 (MHz) and has a bandwidth of 20.46 MHz. In other words, the majority of the intensity of the signal lies at 1575.42 MHz (± 10.23 MHz). The wavelength of the L1 signal is 19 centimeters. (See Figures 4-2 and 4-5.)

2. **L2-RF.** Multiplying the fundamental frequency by 120 generates the Link 2 RF (L2) carrier frequency. It is centered at 1227.60 MHz and has a bandwidth of 20.46 MHz. In other words, the majority of the intensity of the signal lies at 1227.60 MHz (± 10.23 MHz). The wavelength of the L2 signal is 24 centimeters. (See Figures 4-3 and 4-5).

b. Data Sequences. Each GPS satellite develops several binary data sequences transmitted from the GPS control segment. These sequences include the Coarse/ Acquisition Code (C/A-Code), the Precise Code (P-Code), and the Navigation Data Message.

1. **Coarse Acquisition Code.** The Coarse/ Acquisition Code (C/A Code) is sometimes referred to as the Standard Code (S-Code). It has also been called the Clear Access or Civilian Access Code. All GPS satellites on the L-1 carrier wave broadcast it. The transmission of the data sequence is centered at 1575.42 MHz (L-1 Frequency). It is modulated at ± 1.023 MHz providing a bandwidth of 2.046 MHz. The code contains a sequence of 1,023 pseudo-random binary biphase modulations on the GPS carrier at a chipping rate of 1.023 MHz, thus having a repetition period of 1 ms. The C/A-code is a 300 meter measurement wave. (See Figures 4-2, 4-4, and 4-5.)

2. **Precise code.**

a. **General.** The Precise Code (P-Code) is sometimes referred to as the Protected Code. All GPS satellites on both the L-1 and L-2 carrier broadcast it. The transmission of the data sequence is centered at 1575.42 MHz on the L-1 carrier and at 1227.60 MHz on the L-2 carrier. It is modulated at ±10.23 MHz on both carrier frequencies providing a bandwidth of 20.46 MHz. The P-code is a 30-meter measurement wave and can be encrypted by the satellite creating a Y-Code. (See Figures 4-2, 4-3, 4-4, and 4-5.)

Figure 4-2 L-1 Carrier Frequency

Figure 4-3 L-2 Carrier Frequency

Figure 4-4 P and C/A-Code Data Sequence

b. **P-Code Repetition.** The overall P-Code is a mathematically derived binary sequence that is 267 days (approximately 37 weeks) long. It is broken into one-week segments for operational use. Five of these one-week segments are reserved for the GPS control segment. The other 32 segments are available for satellite vehicles (SVs). Therefore, each SV has a unique one-week segment code, which is a subset of the overall P-Code sequence. For this reason, it is generally accepted that the P-Code repeats every week.

Figure 4-5 GPS Signal Data Flow

3. **Navigation Data Message.**

a. **General.** The navigation data message (NAV data) is a 1500 bit navigation message broadcast on either L-1 and L-2 carriers at a rate of 50 bits per second (bps) or 50 Hz. The NAV data message contains system time, clock correction parameters, ionospheric delay model parameters, and the almanac (ephemeris and health data) on the entire constellation. It is broadcast once each hour by each GPS satellite and can be referred to as the D-Code.

b. **Broadcast Format.** The Navigation Data Message is a separate binary data sequence in the satellite; however, the navigation data message is modulated over the C/A and P-Codes for transmission. Each satellite develops the binary code sequence of the C/A Code, the P-Code, and the NAV Data. Since these sequences are all 1's and 0's, the satellite combines the NAV Data with the C/A-Code and with the P-Code to formulate two data streams: one a combination of the C/A code and the NAV Data, the other a combination of the P-Code and the NAV Data. These are the codes actually transmitted on the carrier frequencies. The ground receiver then extracts the NAV Data from the broadcast C/A or P-Code; whichever it was receiving.

4-3 Ephemeris and Almanac Data

Each GPS satellite transmits almanac data once an hour. The almanac data is the position and health status of all satellites in the constellation. The ephemeris is the position data for each individual satellite. There are two types of ephemeris data to be considered: Broadcast and Precise.

a. Broadcast Ephemeris. The broadcast ephemerides are actually predicted satellite positions transmitted as part of the NAV Data message. Any receiver capable of acquiring the C/A or P-Code can acquire the ephemerides in real time. The Master Control Station using past tracking data provided from the five tracking stations computes the broadcast ephemerides. The new orbital parameters are then transmitted back to the satellites once every 24 hours for subsequent transmission to the user segment.

b. Precise Ephemeris. The precise ephemerides are computed from actual tracking data, post-processed to obtain more accurate satellite positions. These ephemerides are available at a later date and are more accurate than broadcast ephemerides because they are based on actual tracking data and not predicted data.

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Section II
SYSTEM SAFEGUARDS AND ERROR SOURCES

4-4 Selective Availability (SA)

a. Purpose. When the concept of GPS was initially developed, it was planned that the Precise Code would be reserved for military use, while the less accurate C/A Code would be authorized for use by anyone. During initial testing of the system it was discovered that while the P-Code measurements provided the expected 10-20 meter accuracy, and the C/A Code provided accuracy as high as 20 meters; much better than the expected 100 meters. The Department of Defense, expecting much lower accuracy determined that a method of introducing errors into the satellite signals was needed to ensure that enemy forces would not be able to obtain high position and timing accuracy from GPS. Selective availability was the outcome.

b. Methods. SA is a method used by the U.S. Department of Defense (DoD) to deny precise position and timing accuracy to unauthorized users. SA uses two methods to intentionally introduce errors into the signals transmitted to the user segment.

1. **Dither.** To alter or manipulate the satellite clocks. This method intentionally introduces timing errors, which ultimately produces position errors at the receiver because of the importance of accurate time to the computation of the pseudorange.

2. **Epsilon.** To alter the orbital parameters (satellite position) which are broadcast in the Almanac portion of the navigation data message. Position error is then created because the receiver is positioned based on the satellite location.

c. Accuracy Levels. The level of accuracy achieved by a GPS receiver is now dependent on whether or not the receiver is equipped with an encryption device, which allows the receiver to accept, and store crypto variables referred to as a key. This key allows the receiver to decrypt SA correction data, which is transmitted in the NAV Data message. This key also allows the receiver to utilize the encrypted P-Code. The two accuracy levels are the Precise Positioning Service and the Standard Positioning Service.

Precise Positioning Service (PPS). The PPS is a precise positioning and timing service that is reserved for the US and allied military, as well as, specific authorized civilian users as long as their receiver accepts the crypto key discussed above. The technical specification is listed at 16 meters Spherical Error Probable (SEP).

Standard Positioning Service (SPS). The SPS is the less accurate positioning and timing service offered to all GPS users. The DoD has stated that this service will be accurate to 100 meters in horizontal position and 150 meters vertical, under normal conditions, 95% of the time. The DoD does have the ability to increase the errors created by SA based upon national security needs.

4-5 Anti- Spoofing (AS)

Anti-Spoofing (AS) is a method used by the DoD to prevent possible hostile imitations of the GPS signal. Encrypting the P-Code creates the Y-Code, which can only be processed by GPS receivers with a valid crypto key. This encrypted code is very difficult to imitate. It is important to understand that the P-Code and the Y-Code are not two separate codes; one is the encrypted version of the other. A GPS receiver without a valid crypto key cannot process the Y-Code and will be limited to measurements from the C/A-Code.

4-6 Cryptovariables

a. General. As stated before, cryptovariables are necessary for a GPS receiver to access the Precise Positioning Service, allowing the receiver to correct for errors caused by SA and AS. It is unauthorized to use a military GPS receiver without a valid crypto fill.

b. Key Materials and Loading Formats. There are three types of key materials available for use with a GPS receiver: Operational Key Material, Maintenance Key Material, and Simulator Key Material. There are also three different formats for key loading.

1. **Operational Key Material.**

a. Two operational cryptographic keys, **Group Unique Variable (GUV) key** and **Crypto- Variable Weekly (CVW) key**, are available for issue to a GPS user. Both the GUV and the CVW keys can be used by a receiver to obtain a daily key (CVd). All Operational Keys are classified CONFIDENTIAL and are marked CRYPTO.

b. The Group Unique Variable (GUV) key is an annual key. It is a Key Encryption Key (KEK), which is used to decrypt previously encrypted daily keys. A GPS receiver loaded with a GUV key takes longer to begin processing navigational data than the weekly key because it must first acquire and decrypt the daily key being broadcast by any GPS satellite. This process could take as long as 12.5 minutes after initial GPS signal acquisition. The GUV key is not a years worth of daily keys, it is merely the data needed by the receiver to decrypt the broadcast daily key.

c. The Crypto-Variable Weekly (CVW) key is sometimes referred to as the Crypto key Weekly (CKW). It is a Key Production Key (KPK), which is used to automatically generate daily keys within the user equipment. Obtaining the daily key from a satellite downlink is not necessary for receivers loaded with a CVW key; therefore, a user with a CVW key will begin processing navigational data in less time than those with a GUV key. Because of this special capability, distribution of the CVW key is limited to those users who demonstrate a valid need for initial GPS acquisition in a minimal amount of time.

d. Both the GUV key and the CVW key will produce the same Daily Crypto-Variable (CVd) key. Once the receiver determines the current working CVd, processing navigational data may commence and the effects of SA and AS can be removed from the GPS signal and full navigational accuracy is restored. A CVd cannot be entered directly into the receiver, only a CVW or a GUV key can be entered. The same CVd is used for both SA and AS.

2. **Maintenance Key Material.** A maintenance key is available to users for troubleshooting the GPS user equipment. The maintenance key does not allow a user to gain access to the daily encryption key. Maintenance keys are unclassified and may be re-used until they are physically unusable.

3. **Simulator Key Material.** A simulator key is available to users for testing receivers. Both the simulator and the equipment must be keyed with the simulator key. The simulator key does not allow a user to gain access to the daily encryption key. Simulator keys are unclassified and may be re-used until they are physically unusable.

4. **Key Loading Formats.** GPS keying materials are provided in three different formats to accommodate various methods of key loading. The **eight-level punched tape format** is used in common COMSEC fill devices such as the KOI-18 General Purpose Tape Reader, the KYK-13 Electronic Transfer Device (capable of loading multiple keys) used in conjunction with the KOI-18, and the AN/CYZ-10 Data Transfer Device (DTD) also used in conjunction with the KOI-18. The **hexadecimal printed format** is used with a GPS data loader or an equivalent NSA approved key loader device. The **decimal printed format** is used with the GPS control display unit. Both the decimal and hexadecimal key formats are commonly referred to as key lists.

c. User Equipment Security. Because of the security classification of the CVW key and GUV key, GPS receivers designed specifically for military use are equipped with a special certified security module that prevents the extraction of cryptographic information from the receiver. These receivers can then remain unclassified even when loaded with a cryptographic key. If classified information other than crypto is stored in the receiver, the receiver becomes classified at the level of the stored information.

4-7 GPS Error Sources

a. General. There are many sources of measurement error that influence GPS performance. The sum of all systematic errors or biases contributing to the measurement error is referred to as range bias. The observed GPS range, the range from the satellite to the receiver, without the removal of biases, is referred to as a biased range or "pseudo-range". Principal contributors to the final range error that also contribute to overall GPS error are ephemeris error, satellite clock and electronic inaccuracies, tropospheric and ionospheric refraction, atmospheric absorption, receiver noise, and multipath effects. Other errors include those induced by the DoD (SA and AS). In addition to these major errors, GPS also contains random observation errors, such as unexplainable and unpredictable time variation. Due to their random nature, these errors cannot be modeled and corrected for. The following paragraphs discuss these errors as they associate with GPS positioning and navigation. Most of these errors are eliminated or their effects significantly reduced when GPS is used in a differential mode because the same errors are common to both receivers during simultaneously observed sessions.

b. Ephemeris Errors and Orbit Perturbations. Satellite ephemeris errors are errors in the prediction of the satellite position, which are then transmitted to the user in the navigation data message. Ephemeris errors are satellite dependent and very difficult to predict and compensate for. This is because the many forces acting on the predicted orbit of a satellite are difficult to measure directly.

c. Clock Error. GPS relies heavily on accurate time measurements. GPS satellites carry rubidium and cesium time standards that are usually accurate to 1 part in 10^{12} and, 1 part in 10^{13}, respectively. Most receiver clocks are actuated by a quartz time standard accurate to 1 part in 10^{8}. The difference between the satellite time and the receiver time is called the time offset. The product of the time offset and the speed of light is equal to the possible error due to clock bias as shown below:

$$R_E = T_O \text{ x } c$$

When R_E is the Range Error due to clock bias
T_O is the Time Offset
C is the speed of light (299,792,458 m/s).

For example, if the time offset is 1 microsecond (10^{-6}) then the RE =10^{-6} x 299,792,458 = 299.8 meters.

d. Ionospheric Delays. GPS signals are electro-magnetic signals, which are dispersed non-linearly and refracted when transmitted through a highly charged environment such as the ionosphere. Dispersion and refraction of the GPS signal is referred to as an ionospheric range effect because the dispersion and refraction of the signal results in an error in the GPS range value. Ionospheric range effects are frequency dependent; in other words the L1 and L2 frequencies are affected differently even though they follow the same path through the ionosphere.

1. The error effect of ionospheric refraction on the GPS range value is dependent on sunspot activity, time of day, and satellite geometry. Periods of high sunspot activity will produce greater range errors than periods of low sunspot activity because of the effects of the Sun's gravity on the ionosphere. Daylight GPS operations will produce greater range errors than nighttime operations. GPS operations with satellites near the horizon will have larger range errors than those with satellites near the zenith because the signal must pass through a larger portion of the ionosphere when the satellite is near the horizon.

2. Resolution of ionospheric refraction can be accomplished with the use of a dual frequency receiver (L1/L2). During a period of uninterrupted observation of the L1 and L2 signals, the signals can be continuously counted and differenced. The resultant difference reflects the variable effects of the ionosphere delay on the GPS signal. Single frequency receivers used in the absolute and differential positioning modes normally rely on an ionospheric model of the typical ionosphere. The use of these models can remove a significant amount of the ionospheric delay.

e. Tropospheric Delays. GPS signals are not dispersed by the troposphere; however, they are refracted. The tropospheric conditions causing this refraction of the signal can be modeled by measuring the dry and wet components.

1. The dry component can be modeled easily through measurement of the surface pressure using the following equation:

$$D_C = (2.27 \text{ x } 0.001) \text{ x } P_O$$

When D_C is the dry term range contribution in ze
P_O is the surface pressure in millibars

For example, if the surface pressure is 765 Mb then the dry term range error is (2.27 x 0.001) x 765 = 1.73655 or 1.7 meters.

2. The wet component cannot be so easily modeled. This is because the wet component is approximated by not only the surface conditions, but by the atmospheric conditions along the entire path of the GPS signal. These conditions include water vapor content, temperature, altitude, and the angle of the signal path above the horizon.

f. Multipath. Multipath is a positioning error caused by the signal arriving at the receiver from more than one path. Generally, this is due to the receiver being located near a reflective surface such as a metal building or structure. Newer antenna designs have some filtering capabilities to reduce the effects of multipath; however, proper mission planning and site reconnaissance is the best way to reduce this type of error. Averaging of GPS signals over a period of time can also reduce the effects of multipath.

g. Receiver Noise. This error source includes a variety of errors associated with the receiver's ability to measure a finite time difference. These include signal processing and filtering, clock/signal synchronization and correlation methods, receiver resolution, signal noise, and electronic interference. Most of these errors cannot be modeled or accounted for.

4-8 User Equivalent Range Error (UERE)

User Equivalent Range Error (UERE) can be referred to as the total budgeted error caused by the error sources listed above. Many of these error sources can be reduced through planning or the use of L1/L2 antennas. The use of differential techniques can even eliminate some of these sources of error. Figure 4-6 lists these errors and biases by associating them with their source segment. The error values in this figure do not include the effects of S/A.

4-9 Absolute GPS Accuracy

a. General. Absolute positions are those, which are established with no reference or tie to any other station, they are sometimes referred to as autonomous. For

Figure 4-6 User Equivalent Range Error

GPS purposes, this is generally accomplished by use of code-phase measurements to determine a pseudo-range. The accuracy of these ranges is largely dependent upon which code (C/A or P(Y)) is being used to determine the position. This range accuracy (i.e., UERE), when coupled with the geometrical relationships of the satellites, result in a 3-dimensional confidence ellipsoid, which depicts uncertainties in all three coordinates. Since the satellites are constantly moving, the geometry constantly changes; therefore, GPS accuracy is time/position dependent.

b. Root Mean Square (RMS) Error Measures.

1. The two-dimensional (2D) (horizontal) GPS position accuracy is normally estimated using a root mean square (RMS) radial error statistic called standard deviation or sigma (σ). A 1-σ RMS (one sigma) error equates to the radius of a circle in which the position has a 63% probability of falling. A circle twice this radius represents an approximate probability of 97 %. This is a 2- RMS or 2DRMS (2-deviations RMS) and is the most commonly used accuracy statistic in GPS survey. In some instances, a 3- RMS (3DRMS) is used to depict a circle three times the radius of the 1-σ circle. This circle has a 99.7% probability. An RMS error statistic represents the radius of a circle and therefore is not defined by a ±.

2. Figure 4-7 depicts RMS on an error ellipse at 2-σ. This ellipse represents a normal distribution of GPS position errors and is centered at the indicated position of the receiver. The radii of an error ellipse are

expressed in standard deviation (sigma (σ)) of the position distribution and usually provide a direction such as Sigma North, Sigma East, and Sigma Up. Each sigma is a probability estimate of how close the actual position is to the displayed position as discussed.

Figure 4-7 Error Ellipse at 2-σ RMS

c. Probable Error Measures.

1. In two-dimensional (2D) horizontal positioning, a Circular Error Probable (CEP) statistic is most commonly used, especially in military targeting. CEP refers to the radius of a circle with a 50% probability of position confidence. In other words, a measured or calculated position will fall inside a circle of some radius at least 50% of the time.

2. Three-dimensional (3D) GPS accuracy is most commonly expressed as a Spherical Error Probable (SEP). This value represents the radius of a sphere with a 50% confidence level or probability. It is important to understand that this sphere only approximates an actual 3D error ellipsoid that represents the uncertainties in the geocentric coordinate system.

d. Dilution of Precision (DOP). Dilution of Precision is a scalar quantity representing the contribution or effect of the satellite geometry to the GPS accuracy. It is the ratio of the standard deviation of one coordinate to the measurement accuracy. It could be said that DOP is the measure of the strength of the satellite geometry. In general, the more satellites that are observed and used in the final solution, the better the solution. Since DOP can be used as a measure of geometric strength, it can also be used to determine which satellites a receiver can use to determine the most accurate position.

1. **Satellite Geometry and DOP.** Satellite Geometry and DOP can best be visualized by the following analogy. A rubber ball is suspended from five strings; all five strings are attached at the other end to the ceiling within a couple meters of each other. Because of poor geometry of the strings' attachment to the ceiling, the ball can be moved easily. A large portion of the possible error in the position of the ball is due to poor geometry or, high Dilution of Precision. On the other hand, if the ball was still attached to the same strings, but four of the strings were attached to the ceiling at the four corners of the room and the fifth string attached directly above the ball, the ball would not move so easily. This would be due to strong geometry and the Dilution of Precision would be small.

2. **Geometric Dilution of Precision (GDOP).** The main form of DOP used in measuring absolute accuracy is the Geometric Dilution Of Precision (GDOP). GDOP is the measure of accuracy of three-dimensional position and time. GDOP is related to actual range error by stating that the actual range error is equal to GDOP multiplied by the UERE.

3. **Position Dilution of Precision (PDOP).** PDOP is the measure of the accuracy in 3D position only.

a. PDOP values are generally developed from satellite ephemerides prior to the conduct of survey operations. When this is done, the surveyor can more adequately plan sessions and occupations for his equipment.

b. PDOP represents the position recovery at a particular instance in time and is not representative of the entire session. PDOP error is generally given in units of meters of error per 1-meter error in pseudo-range measurement (i.e.. m/m). In other words, if the pseudo-range measurement due to clock errors, atmospheric conditions, etc. is in error by 2 meters and the PDOP is 5.5, the possible position error due to satellite geometry is 11 meters. When using pseudo-ranging techniques for absolute positioning (code phase), PDOP values lower than 5 m/m are considered very good, values greater than 10 m/m are very poor. For static type surveys, it is desirable to make observations during periods of rapidly changing PDOP.

c. When the values of PDOP and GDOP are observed over time, high values (> 10 m/m) can be associated with poor geometry. The higher the PDOP, the poorer the solution for that instant in time. Poor geometry can be the result of satellites being in the same plane, orbiting near each other, or at similar elevations.

4. **Horizontal Dilution of Precision (HDOP).** HDOP is a measurement of the accuracy in 2D horizontal position. It is significant in evaluating surveys intended for horizontal control. Basically, HDOP is the RMS position error divided by the standard error in the range measurements. It roughly indicates the effects of satellite range geometry on a resultant position. HDOP values lower than 3 indicate the best geometry.

geometry.

6. **Time Dilution of Precision (TDOP).** TDOP is the measurement of the accuracy of the time determined by the GPS receiver.

Section III
GPS Measurements

4-10 GPS Reference System

The GPS satellites reference their own position to the WGS 84 coordinate system. This system is based on the WGS 84 ellipsoid. The Earth rotates on an axis, but that axis is not constant, it "wobbles" much like a spinning top. In order to fix the Earth in time and space for the development of the WGS 84 ellipsoid, the Conventional Terrestrial Pole of 1984 (CTP 84) was chosen. In other words, the position of the Earth's polar axis at 1984.0 as defined by the Bureau International De l'Heure (BIH) is used to define the Z-axis of the WGS 84 Cartesian coordinate system. The X and Y-axes are then referenced to that Z-axis. All positions determined by GPS are originally in this format, WGS 84 Cartesian. Receivers and software applications for GPS have the capability to provide positions in other coordinate systems and other datum/ellipsoid references.

4-11 Code Phase Measurements

a. General. The primary purpose of Code Phase measurements is to determine approximate ranges from satellites to the GPS receiver, which will allow the

5. **Vertical Dilution of Precision (VDOP).** VDOP is a measurement of the accuracy in standard deviation () in vertical height. Mathematically, it is the (Sigma Up) divided by UERE (around 6 meters with P(Y)-code and 12 meters with C/A-code). A VDOP value lower than 3 indicates a strong vertical component in the

receiver to determine its position. Since this position is not referenced or relative to any other position or receiver, it is referred to as an **absolute position**. Clock biases, atmospheric absorption and refraction, and other inherent errors make determination of a true range virtually impossible; the actual range that is determined by the GPS receiver is referred to as a **Pseudo-range**.
(See Figure 4-8.)

b. Pseudo-random Noise (PRN) Code. The PRN-code is a binary data string of digital ones and zeros, which is unique to the satellite broadcasting it. This code is used by the receiver to identify the satellite it is tracking. This code is repeated every millisecond (C\A), and every week (P\Y). (See Figure 4-8.)

Figure 4-8 Psuedo-range

Figure 4-9 Carrier Modulated by PRN

c. Time Delay. Before the receiver can compute the pseudo-range to the satellite, it must determine the time required for the signal to travel from the satellite to the antenna. The receiver stores a replica of each satellite's PRN-code. When the receiver detects a satellite signal, it identifies the satellite by its PRN, which has been replicated from memory. The code received from the satellite is then compared to the replicated code. The receiver "slides" the replicated code in time until it lines up with the satellite's transmitted code. The amount of time that was needed to slide the code is the time delay of the transmission or travel time. (See Figure 4-10.)

Figure 4-10 Time Delay of a GPS Signal

d. Satellite Ranging.

1. The only measurement made by a code-phase receiver is the time delay, or transmission time. Radio waves travel at the speed of light; this constant value is stored in the memory of the GPS receivers. A receiver capable of making code-phase measurements will compute the pseudo- range using the following formula:

Pseudo-range =Δ t x speed of light

This procedure can be simultaneously performed on many satellites. The number of satellites is dependent on the receiver being used, or more specifically, how many channels are available in the receiver.

Figure 4-11 Ranging One Satellite

2. Once a satellite is tracked and the receiver determines a pseudo-range, the receiver basically knows it is located on a sphere whose radius is equal to the pseudo-range with the satellite at the center of the sphere. (See Figure 4-11.)

3. When the second satellite is acquired, the same ranging technique is used creating a second sphere. The intersection of the two spheres is a circle; the receiver is located somewhere along the edge of that circle. (See Figure 4-12.)

Figure 4-12 Ranging Two Satellites

4. The third sphere determined by ranging a third satellite would intersect the circle created above at two points. The receiver knows that its position is referenced to the WGS-84 ellipsoid/datum. Only one of the two points of intersection will be located on this geodetic system, the other point will be out in space, deep inside of the ellipsoid, or moving at an extreme velocity. With three satellites, a receiver can be capable of providing a two dimensional position.

Figure 4-13 Ranging Three Satellites

5. In order to achieve a three-dimensional position, at least four satellites must be ranged. This fourth satellite will provide the necessary timing data needed for the receiver to resolve timing errors in the system.

4-12 Carrier Phase Measurements

a. General. The primary purpose of Carrier Phase measurements is to determine ranges from satellites to receivers, which will allow the receiver to position itself. Usually these positions are processed relative to another receiver position and are referred to as differential positions. The ranges to the satellites are pseudoranges, as in code phase; however, this method of ranging requires the solution of the integer ambiguity of the signal. In other words, the determination of this distance requires that the number of whole carrier wavelengths be known.

b. Integer Ambiguity. The whole number of wavelengths between the satellite and the receiver is known as integer ambiguity or cycle ambiguity. Since we know the L1 carrier wavelength is 19 cm long and L2 is 24 cm long, and since most carrier phase receivers can determine the partial wavelength to an accuracy around 2 mm; the pseudorange can be accurately measured as long as we can determine the number of complete wavelengths between the satellite and receiver. This is done by comparing changes in the received frequency (caused by the Doppler effect) to the broadcast frequency over time.

c. Carrier (Beat) Phase. Carrier phase GPS receivers contain an internal oscillator, which generates a carrier signal. This generated carrier signal is compared to the received signal from the satellite. The carrier phase observations (also called carrier beat phase) are determined from these measurements.

d. Continuous Carrier Phase.

1. When the receiver first locks on to a satellite signal, it can only measure the fractional part of the wavelength. It has no knowledge of the number of full wavelengths at that specific point in time between it and the satellite. After that first measurement, the receiver will count the number of whole wavelengths it observes. This is the continuous carrier phase.

2. If the satellite signal is interrupted (see Cycle Slips below), the continuous carrier phase is reset. It is set to the next fractional wave measurement (carrier phase observable) immediately following the break.

e. Cycle Slips. A cycle slip is the interruption or break in the continuous carrier wave.

1. The wave fronts that are counted by the receiver during continuous phase tracking are called cycles. When the signal is interrupted, the continuous count of those wave fronts or cycles is broken, or the count slips. This cycle slip causes the continuous carrier phase to be reset. The baseline processor in most GPS-S systems can reestablish this count whether in a static or a kinematic mode.

2. Cycle slips can be caused by any number of barriers between the satellite and the receiver. These barriers can include terrain masks, trees, or even an operator standing between the satellite and the antenna. Cycle slips could be caused by burst jamming signals. In most cases, reconnaissance, line of site clearing, and planning can eliminate many sources of cycle slips.

4-13 Differencing

a. General. Differencing is a method used by the processors to solve for the first estimation of a baseline solution and remove measurement errors. There are three different processing modes: Single Differences, Double Differences, and Triple Differences.

b. Single Differences.

1. Between Receivers. A single difference can be formed by differencing the measurements acquired by two receivers observing the same satellite at a particular point in time or epoch, and integer ambiguities associated with each receiver are combined. Single differences between receivers virtually remove all satellite dependent errors such as satellite clock error, and to a large extent, orbit errors and atmospheric delays. (See Figure 4-14.)

Figure 4-14 Single Differences Between Receivers

2. **Between Satellites.** Differencing measurements acquired by one receiver observing two satellites at a particular point in time or epoch can form a single difference. Single differences between satellites reduce most receiver dependent errors. (See Figure 4-15.)

Figure 4-15 Single Differences Between Satellites

c. Double Differences (Between Satellites and Receivers). Differencing two single differences forms a double difference. This involves two receivers observing the same two satellites at the same epoch. Four separate measurements and four separate integer ambiguities are combined to create a difference. The double differencing mode removes most of the effects of satellite and receiver clock drift. (See Figure 4-16.)

Figure 4-16 Double Differencing

d. Triple Differences (Between Satellites, Receivers, and Time).

1. A triple difference is determined by combining two double differences over time. In other words, the double difference determined by a set of satellites and receivers at a particular epoch is combined with the double difference form the same satellites and receivers at a different epoch. In this mode, integer ambiguities cancel out of the computations because it does not change over time. (See Figure 4-17.)

Figure 4-17 Triple Differencing

2. Triple differences are often used to find cycle slips. A cycle slip, in the single differencing mode, causes the receiver to recompute the combined integer; therefore, after a cycle slip, the integer ambiguity does change. A large change in the triple difference is a good indicator of a cycle slip at that epoch.

4-14 Baseline Solutions

a. General. A baseline solution (vector) is a straight line defined by its 3-dimensional ($\Delta X, \Delta Y, \Delta Z$) values when one end of the vector is the origin and the other end is the point containing those relative values.

1. The processor uses the differencing methods described above along with code solutions to determine an initial estimate of the baseline vector. This initial estimate is called the **triple difference solution**.

2. If we can determine the integer ambiguity, we can multiply that value by the wavelength (19cm - L1, 24 cm - L2) and add the partial wavelength to obtain the pseudo-range. At this point in the processing, the integer ambiguity is still an unknown value.

b. Float Solution. Since we have determined an initial estimate of the baseline vector, we can place that value in the formula:

$$\Delta X, \Delta Y, \Delta Z = (N \times \lambda) + \Delta\phi$$

Whereas: $\Delta X, \Delta Y, \Delta Z$ is the baseline vector,
N is the integer ambiguity,
λ is the wavelength,
ϕ is the phase change observed in a small portion of the data.

1. Often in processing, the value for N as determined in the above formula is not an integer. The ambiguity computes to a value such as 500.52. This value is not close enough to a whole integer for the processor to determine if the ambiguity is 500 or 501; therefore, it cannot set the value to a whole integer.

2. The value determined is compared against the remaining observations to see how well it "fits". If the residuals (errors) are within a certain tolerance, the processor generates a new baseline vector, the **float solution**.

c. Fixed Solution. A fixed solution is obtained when the processor determines a set of integer values for the ambiguity that is significantly better than the other values.

1. The processor rounds the ambiguity value determined above to whole numbers for each satellite, each time testing different combinations of whole wavelength values to compute a baseline.

2. Each time a new set of integers is used, an associated **variance** (square of the standard deviation) is generated. After all possible combinations of whole wavelengths have been tried, the processor selects the solution with the lowest variance (least error); this is the **fixed solution** or fixed-integer solution.

3. The ratio of the errors between the integers used for the last iteration (the last computation of whole integer values) can be determined as follows:

$$\text{Ratio} = \frac{\textit{(integers giving next least) Errors}}{\textit{(integers giving least) Errors}}$$

4. With a single frequency receiver, this is the best solution that can be determined; it is sometimes referred to as a **double-difference fixed solution**.

5. With a dual-frequency receiver, it is possible to combine carrier phase observables to create other fixed solutions.

a. **Widelane Fixed Solution.** A widelane carrier phase is generated when the processor differences the carrier phase observables (L1-L2). The effective wavelength is 86.2 centimeters. This combination allows for easier resolution of the integer ambiguities so it is often used to solve long baselines.

b. **Narrowlane Fixed Solution.** The narrowlane carrier phase is generated when the processor combines the carrier phase observables (L1+L2). The effective wavelength of the narrowlane carrier phase is 10.7 cm. This combination is very effective for canceling out ionospheric errors.

c. **Ionospheric Free Fixed Solution.** This baseline solution uses a combination of the L1 and L2 carrier phases to model and remove the effects of ionospheric interference on the signals. This is the optimal solution, used for high-order control networks and for observing long baselines.

4-15 GPS Survey Methods

a. Absolute Positioning.

1. Absolute positioning is a GPS survey method, which involves the use of a single passive receiver (e.g. AN/PSN-11 PLGR, AN/PSN-13 4000 MSGR). The term absolute does not refer to a specific accuracy, but to the fact that this method does not rely on any source of information other than what is collected by the receiver at that station. This position is not relative (common) to any other station and the accuracy of this position is dependent on many different error sources as well as the user's level of authorization (PPS or SPS).

2. The receiver collects data from multiple satellites and will use this data to determine position, velocity, and timing information. The position is generally determined from code phase measurements; however, some receivers are capable of using carrier phase measurements to determine absolute positions.

b. Differential (Relative) Positioning.

1. General.

a. Differential positioning is a GPS survey method, which requires that at least two receivers collect data from at least 4 common satellites simultaneously to compute a vector between the two receivers. The vector is then fixed at one end to a point and the other end is the relative position.

b. Usually, one of the receivers will be located at a "known" point. Depending on the differential technique used, more than four common satellites may be necessary. Processing the collected data can be performed either in the office or by the receiver in the field, also dependent on the differential technique used.

c. Much of the accuracy achieved from this method of GPS survey is due to the use of common satellites and common epochs (a specific point of time selected for a GPS measurement). Figure 4-6 shows that differential techniques negate most sources of error; this is because the same error exists at each station collecting data from a specific satellite at a specific epoch. In other words, the errors broadcast by satellite PRN23 and collected by receiver A at epoch 1 are the same errors collected by receiver B at epoch 1. Therefore, the errors broadcast from the satellites have no effect on the dimensions of the vector because the errors are equal at each end.

d. This is actually only true for error sources in the Space and Control segments. User segment error sources are not always equal at each end of the vector. For distances under a reasonable length (25-30 Km), the tropospheric and ionospheric errors are basically the same; in other words, the signals from satellite PRN23 to receiver A travel through the same sampling of the atmosphere as the signals from PRN23 to receiver B. Larger distances may add some small errors into these measurements; however, the use of an L1/L2 antenna will decrease this error.

2. Code Phase Differential Positioning. Determining differential positions from code phase measurements is performed by applying a correction to the pseudo-range determined from an individual satellite to the receiver.

a. This process begins with the pseudo-ranges from code phase measurements used to determine the absolute positions of the receivers. Since the errors collected at each receiver are the same for each epoch, a pseudo-range correction (PRC) can be computed. In other words, let's say we know the exact position of a satellite at a specific epoch and the surveyed position of a GPS receiver; we can determine a true range. If the measured pseudo-range is 79 meters and the true range is 81 meters, the PRC is +2 meters. A pseudo-range correction can be generated for each satellite being observed. Any receiver that is simultaneously collecting data from at least four common satellites can apply the PRC to its pseudo- range measurements to obtain a relative (common) position; thus the distance between the two points will be relatively accurate (0.5-10 meters) even when the absolute positions are not.

b. Code phase differential positioning has its primary applications in real-time navigation where relative accuracy as low as 10 meters is acceptable. Also, some engineering survey applications can tolerate this accuracy. This would not be acceptable for geodetic applications, and does not meet artillery specifications.

3. **Carrier Phase Differential Positioning.** Determining differential positions from carrier measurement is as simple as fixing an end of a measured vector to determine the position of the other end. Through processing, other vectors can then be

fixed to the end of the first vector to create a network. Kinematic and static surveys are both usually performed using carrier phase differential positioning.

4-16 GPS Survey Techniques

a. General. When GPS receivers are used for surveying purposes, it is generally accepted that the survey will be performed using carrier phase differential (relative) survey methods. Differential survey is usually divided into two techniques: Static and Kinematic. The following paragraphs provide a basic explanation of these techniques. The MSGR Job Aid provides more in depth discussion of these techniques as they apply to the Trimble 4000 MSGR (AN/GSN-13).

b. Static Survey. Static surveys provide the most accurate results. In this technique, receivers must remain stationary (static) for a period of time dependent on the type of static survey performed. Two types of static survey are generally considered: Static and Fast Static. Both types require extensive planning and post-processing. Static survey allows for extremely accurate networking of survey control. Due to the planning, fieldwork, and post-processing requirements, artillery surveyors whose mission is to provide fourth order control should only use this technique.

c. Kinematic Survey. Kinematic surveys provide accuracy results sufficient for most artillery survey missions (4th and 5th order), but do not provide the same networking capabilities as static techniques. Two types of kinematic surveys are generally considered: Stop-and-Go and Continuous. Stop-and-Go surveys can be post-processed in the office PCs or in the field by the receivers using Real Time Kinematic (RTK) and Real Time Kinematic/On the Fly (RTK/OTF) procedures. Kinematic survey techniques require that one receiver remains static while another receiver acts as a "rover", moving along a route or from station to station collecting data.

4-17 Vulnerabilities/Survivability

The GPS design process required consideration of certain system vulnerabilities. These vulnerabilities are generally grouped by the GPS segment they threaten.

a. Space Segment.

1. **Anti-satellite Weapons (ASAT).**

a. The height of the GPS satellites (10,898 miles) is outside the range of current Anti-satellite weapons. Such space weapons would be deployed at lower altitudes where they could possibly be used against more attractive space based systems. The constellation generally keeps the satellites approximately 44,000 Km apart in each orbital plane and the control segment manages the system so that no two satellites will orbit within 8,100 Km of each other. This spatial separation ensures that a single nuclear burst in space at half the closest distance will have little effect forcing a more direct assault against individual satellites. A ground-launched attack by ASAT would be detected early enough in the three-hour flight time to allow for maneuvering of satellites.

b. It is unlikely that current or projected technology would allow a nation to launch a direct attack or even detonate a nuclear device in the GPS orbit. A nuclear detonation in space would equally affect other space based systems with a blackout or scintillation effect lasting ten minutes or longer in the L-band. This detonation would disturb the atmosphere and the ionosphere with subsequent effects on propagation; also the effects of radiation could incapacitate the functioning of the erasable read only memories (EROMS) and random access memories (RAMS) of these systems if the blast is sufficiently close. For the GPS satellites, there exists built-in protection against the electromagnetic pulse (EMP) caused by nuclear detonations and there is a capability to restore their erased memories through the control segment.

c. Two other factors exist that add an unplanned edge of survivability against ASAT. The first is the Russian GLONASS system. The GLONASS system orbits at an altitude close to the GPS orbit. A nuclear assault against GPS would have the same effect on GLONASS. The second unplanned factor is the increased use of GPS by former Eastern Block nations including the former Soviet Union.

2. **Lasers**. Since the introduction of the Strategic Defense Initiative (SDI), lasers have become a planned vulnerability to orbiting satellites. Limited laser hardening of the satellites enhances survivability of GPS against laser technology. Additionally, a space-based laser at low altitudes would be an extremely heavy device to launch. The tracking and targeting of a GPS satellite is extremely difficult due to its relatively small size and its orbital rate (14,500 Km/hr). Technology is available for a high power ground based laser to target and have a limited effect on GPS satellites.

3. **Replenishment**. Should there be a loss of any GPS satellite, replenishment from the ground can be

accomplished within 2 months. The system can operate fully even with the loss of nine or more satellites, still providing 3D coverage a full 12 hours and 2D coverage more than 20 hours.

b. Control Segment. This is considered by many to be the most vulnerable segment of GPS. The Master Control Station, located in Colorado Springs Colorado, is very well protected being collocated with several military bases; however, the tracking stations do not have this advantage. All the stations are susceptible to espionage and natural disasters, but the tracking stations are much more vulnerable to nuclear and conventional assaults. These factors have been considered, and although the ability exists to exert complete control over the satellites from the Master Control Station, the uplink to each satellite will be less frequent than the current 8 hours. Next generation satellites are planned to provide a cross-link ranging capability, which will allow satellites to communicate with each other, making the offshore tracking stations redundant. Jamming of the control segment between the tracking stations and the Master Control Station is a real possibility; however, all four tracking stations would have to jam simultaneously to be effective.

c. User Segment.

1. Only two major vulnerabilities exist with the user segment, key security and jamming. Key security is discussed below. Jamming is considered so important that it will be discussed separately as its own topic.

2. **Cryptographic Key Security.** Should the enemy capture a GPS receiver with a valid crypto fill, the PPS-security module prevents reverse engineering, so that the enemy cannot gain access to the cryptographic data stored inside the receiver. Also, the regular change of crypto keys adds to the security and survivability of the system.

4-18 Jamming in GPS

a. Types of Jammers. There are several types of jamming that can be used against GPS receivers. Only four will be discussed:

1. Spoofing (Deception Jamming)
2. Continuous Wave (CW) Jamming
3. Wide Band Jamming
4. Pulse/Amplitude Modulated Jamming

1. **Spoofing.** Spoofing is classified as the enemy's attempts to duplicate or imitate GPS signals.

a. Spoofing requires that the enemy have knowledge of the received satellite phase and frequency at the targeted receiver antenna. The proper carrier frequency and timing code phase plus a sufficiently higher power output will allow a deceptive jammer to establish a false lock with the receiver. Also, the enemy must know which satellites are being tracked as well as the position and velocity of the receiver to be able to create a false signal that will have the correct Doppler shift. Once false lock is established, the spoofer can perturb the duplicated navigation signals to cause navigation errors.

b. When GPS anti-spoofing protection is enabled, spoofers cannot autonomously generate the signals needed to deceive the receiver looking for the encrypted P-code. This technique transforms the P-code by cryptographic means. The resultant bit stream is a cipher text called the Y-code that replaces the P-code in its entirety. Receivers with a valid crypto key will encrypt their own generated P-code to produce a Y-code inside the receiver needed for correlation with the satellites transmitted Y-code. The C/A code is totally unaffected by the P-code encryption. For this reason, the C/A-code is very susceptible to deception jamming.

2. **Continuous Wave (CW) Jamming.** A CW jammer, or Spot Jammer, will concentrate its jamming power in a very narrow band around the L1 or L2 carrier. In the GPS receiver the jamming power will be spread out according to the receiver "processing gain" using the modulated C/A- or P-code. After this spreading occurs, only a small portion of the jamming power will enter the tracking loops of the receiver. Consequently, a CW (Spot) jammer needs to be very powerful in order to effectively jam a GPS receiver.

3. **Wide Band Jamming.** A Wide Band Jammer needs a sufficiently wide spectrum in order to cover the frequency band of the GPS signals. In most cases, wide band jamming is performed in either a sweeping mode or a quasi-random noise (barrage) mode. In a sweeping mode, the jammer carrier is moved rapidly and possibly randomly through the band to be jammed. In the case of "barrage" jamming; however, the spectral power density is low compared with spot jamming.

4. **Pulse/Amplitude Modulated Jamming.** A Pulse jammer switches its power on and off during an operation cycle. The modulation rate can be chosen as needed (pulse repetition frequency and pulse duration). An Amplitude Modulated jammer varies its power linearly and modulation depth and frequency can be chosen as needed. Besides jamming effects already described, this type of jamming could have a negative impact on the GPS receiver by disturbing the internal

operating cycles of the receiver processor unit or the electronics of the antenna.

b. Jamming Effects on Code Acquisition. Three modes of acquiring the GPS signal will be considered: C/A-code acquisition, P(Y)-code acquisition, and P(Y)-code reacquisition.

1. **C/A-code Acquisition.** The GPS user is at a severe disadvantage when having to use C/A-code acquisition in a hostile region. Current technology receivers have only a limited tolerance to jamming during C/A-code acquisition (usually around 25 dB). Although only 1023 chips must be searched in the C/A-code, a large frequency window must be searched to account for satellite and receiver Doppler shift. The receiver must maintain a large predetection bandwidth in order to acquire the C/A- code at the expense of reduced jamming tolerance (J/S). The C/A-code is widely disseminated, so a smart jammer can broadcast a false signal and lock up the receiver with very low power. Tests have indicated that a very modest one watt noise jammer can prevent a receiver from acquiring the GPS signal using the C/A-code out to a range of 85 Km. If the jammer were to transmit a spoofing signal, the receiver would not be able to discriminate between the desired GPS signal and the spoofing signal; therefore, the receiver's jamming tolerance would be on the order of 0 dB, a one watt spoofer could deny C/A-code acquisition past 1000 Km or to the jammer's horizon.

2. **P(Y)-code Acquisition.** The P(Y)-code is virtually impossible for an adversary to spoof because of its long length and the encryption of the P-code into the Y-code. Also, the P(Y)-code has 10 dB more anti-jam protection than the C/A-code because of its 10 times larger bandwidth. Some current technology receivers using direct P(Y)-code acquisition (hot start) can tolerate a J/S level in excess of 35 dB. However, because the P(Y)-code is so long, (approximately 6×10^{12} chips) much time or more correlators operating in parallel are needed for the two-dimensional search over code timing and Doppler frequency. Thus, up to date satellite ephemerides and accurate code timing must be available to effectively perform a hot start.

3. **P(Y)-code Reacquisition.** Reacquisition typically has very accurate initial code timing. If this accuracy is available during direct P(Y)-code acquisition, the reacquisition problem is the same as the acquisition problem with increased J/S tolerance (in excess of 50 dB dependent on the receiver).

c. Anti-jam Capabilities of GPS. GPS vulnerability to jamming can never be completely eliminated. With constantly improving techniques and technology, higher power outputs by the enemy jammers are required to deny access to GPS signals.

1. **Line of Sight Limitations.** The GPS satellites broadcast in the Ultra-High Frequency (UHF) domain. UHF signals cannot "go around" obstacles such as buildings, hilltops, large rocks, etc. the way low domain frequencies can. For this reason, ground based jammers are restricted by severe line-of-sight limitations. Air or space borne jammers, obviously, are not so restricted. A smart user will position his GPS receiver as to limit the effects of a line-of-sight jammer. Defilade areas, which still allow open skies for satellite signals, can be used. Handheld receivers can be placed in a "cathole" or the user can simply turn his back to the suspected direction of the jammer. Once the receiver has a lock on the P(Y)-code, the user should be able to operate normally in most jamming environments.

2. **Inherent Receiver Anti-jam Capabilities.**

a. The satellite signal is a continuous wave type signal. This signal is spread by modulation and enters the receiver with the jamming signal. The original signal is recovered as the jammer energy is spread over the modulation and most of the jammer power is filtered out.

b. To be able to locate, track, and demodulate a satellite signal, the receiver requires a certain minimum ratio between received signal power and the noise power. This value, or threshold, is referred to as the Signal-to-Noise ratio (SNR or C/N). The noise power is dissipated over a wide bandwidth, while the satellite signal power is concentrated in a very narrow frequency band. Using filters, the GPS receiver narrows its bandwidth to the absolute minimum in order to receive the maximum signal power and minimum noise. A receiver can usually recognize the jammer power as noise; therefore, much of its effects are filtered out. Dependent on the power output of the jammer, the SNR may be too high for the receiver to filter out enough noise to determine data.

3. Many other Anti-jam capabilities exist for GPS. Among them, Inertial Navigation System (INS) integration with GPS and high cost antennas. Both used in military applications but generally with missile, rocket, and aircraft navigation technologies. For the most part, anti-jam capabilities for Marine ground units will be enhanced by proper planning and positioning of GPS assets.

4-19 Additional Considerations.

1. In addition to the previously stated limitations and possibilities for jamming; the Surveyor must be aware of the ambient conditions of the GPS satellites and their surrounding environment.

2. Solar flares, occurring in 11-year cycles, send great fountains of electromagnetic energy and radiation deep into space, causing interference in GPS signals.

3. Meteor showers, such as the Leonid event, occur close to the Earth, and could potentially damage satellites in the GPS constellation.

4. The GPS satellites are hardened against such possibilities, but they are not invulnerable.