PUBLIC RELEASE VERSION

NAVSTAR GPS

USER EQUIPMENT

INTRODUCTION

SEPTEMBER 1996

PUBLIC RELEASE VERSION

CONTENTS

Page

CONTENTS (Continued)

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

ILLUSTRATIONS

Figure **Page**

TABLES

Table **Page**

CHAPTER 1: SYSTEM OVERVIEW

1.1 GENERAL DESCRIPTION

The Navstar Global Positioning System (GPS) is a space-based radio-positioning and time-transfer system. GPS provides accurate position, velocity, and time (PVT) information to an unlimited number of suitably equipped ground, sea, air and space users. Passive PVT fixes are available world-wide in all-weathers in a world-wide common grid system. Normally GPS contains features which limit the full accuracy of the service only to authorized users and protection from spoofing (hostile imitation).

GPS comprises three major system segments, Space, Control, and User (see Figure 1-1).

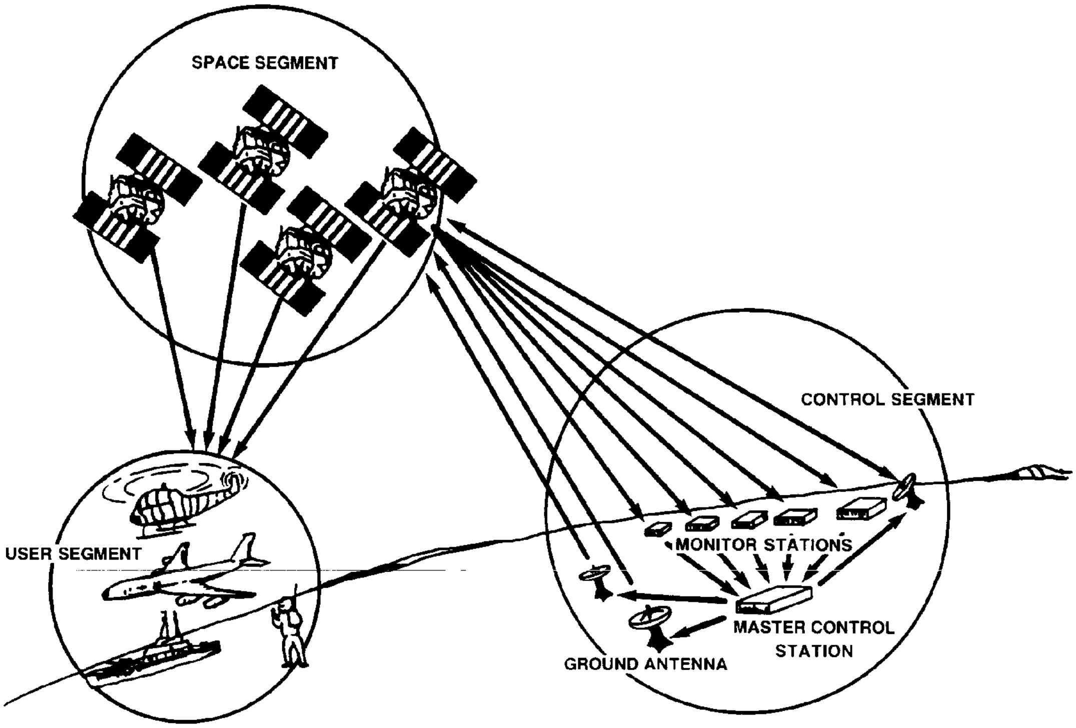


Figure 1-1. Navstar GPS Major Segments

The Space Segment consists of a nominal constellation of 24 Navstar satellites. Each satellite broadcasts RF ranging codes and a navigation data message. The Control Segment consists of a network of monitoring and control facilities which are used to manage the satellite constellation and update the satellite navigation data messages. The User Segment consists of a variety of radio navigation receivers specifically designed to receive, decode, and process the GPS satellite ranging codes and navigation data messages. The Space, Control, and User Segments are described in more detail in paragraph 1.2.

The ranging codes broadcast by the satellites enable a GPS receiver to measure the transit time of the signals and thereby determine the range between each satellite and the receiver. The navigation data message enables a receiver to calculate the position of each satellite at the time the signals were transmitted. The receiver then uses this information to determine its own position, performing calculations similar to those performed by other distance-measuring navigation equipment. Conceptually, each range measurement defines a sphere centered on a satellite. The common intersection point of the spheres on or near the earth's surface defines the receiver position.

For GPS positioning, a minimum of four satellites are normally required to be simultaneously "in view" of the receiver, thus providing four range measurements. This enables the receiver to calculate the three unknown parameters representing its (3-D) position, as well as a fourth parameter representing the user clock error. Treating the user clock error as an unknown enables most receivers to be built with an inexpensive crystal oscillator rather than an expensive precision oscillator or atomic clock. Precise time estimates are required for precise positioning, since a time error of 3 nanoseconds is roughly equivalent to a range error of 1 metre. Less than four satellites can be used by a receiver if time or altitude is precisely known or if these parameters are available from an external source. A more detailed explanation of the GPS theory of operation is provided in paragraph 1.4.

1.2 SYSTEM OVERVIEW

1.2.1 Space Segment

The GPS Space Segment consists of 24 Navstar satellites in semi-synchronous (approximately 12-hour) orbits. The satellites are arranged in six orbital planes with four satellites in each plane. The orbital planes have an inclination angle of 55 degrees relative to the earth's equator. The satellites have an average orbit altitude of 20200 kilometres (10900 nautical miles) above the surface of the earth. Figure 1-2 illustrates the GPS satellite constellation.

The satellites complete one orbit in approximately 11 hours and 58 minutes. Since the earth is rotating under the satellites, the satellites trace a track over the earths surface which repeats every 23 hours and 56 minutes. A user at a fixed location on the ground will observe the same satellite each day passing through the same track in the sky, but the satellite will rise and set four minutes earlier each day, due to the 4 minute difference between the rotational period of the earth and two orbital periods of a satellite. The satellites are positioned in the orbital planes so that four or more satellites, with a good geometric relationship for positioning, will normally be observable at every location on earth. The effect of geometric relationships on GPS positioning accuracy is explained in further detail in Chapter 3

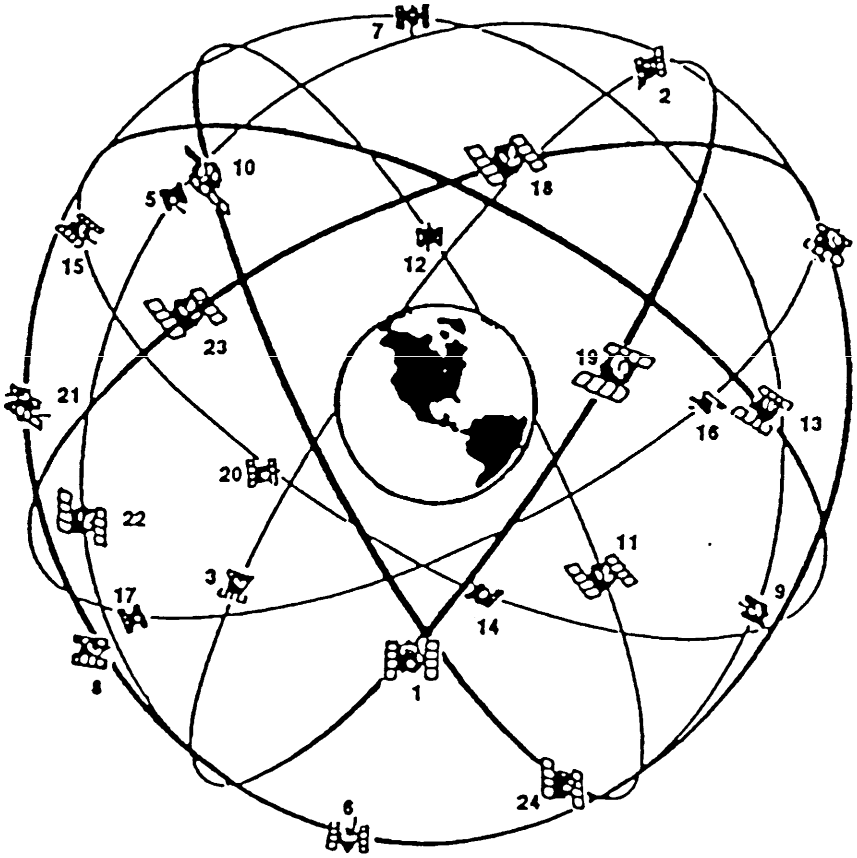


Figure 1-2. GPS Satellite Constellation

The satellites transmit ranging signals on two D-band frequencies: Link 1 (Ll) at 1575.42 MHz and Link 2 (L2) at 1227.6 MHz. The satellite signals are transmitted using spread-spectrum techniques, employing two different ranging codes as spreading fictions, a 1.023 MHz coarse/acquisition code (C/A-code) on L1 and a 10.23 MHz precision code (P-code) on both L1 and L2. Either the C/A-code or the P-code can be used to determine the range between the satellite and the user, however, the P-code is normally encrypted and available only to authorized users. When encrypted, the P-code is known as the Y-code. A 50 Hz navigation message is superimposed on both the P(Y) -code and the C/A-code. The navigation message includes satellite clock-bias data, satellite ephemeris (precise orbital) data for the transmitting satellite, ionospheric signal-propagation correction data, and satellite almanac (coarse orbital) data for the entire constellation. Refer to paragraph 1.4 for additional details regarding the ranging codes and navigation message.

1.2.2 **Control Segment**

The Control Segment primarily consists of a Master Control Station (MCS), at Falcon Air Force Base (AFB) in Colorado Springs, USA, plus monitor stations (MS) and ground antemas (GA) at various locations around the world. The monitor stations are located at Falcon AFB, Hawaii, Kwajalein, Diego Garcia, and Ascension. All monitor stations except Hawaii and Falcon AFB are also equipped with ground antennas (see Figure 1-3). The Control Segment includes a Prelaunch Compatibility Station (PCS) located at Cape Canaveral, USA, and a back-up MCS capability.

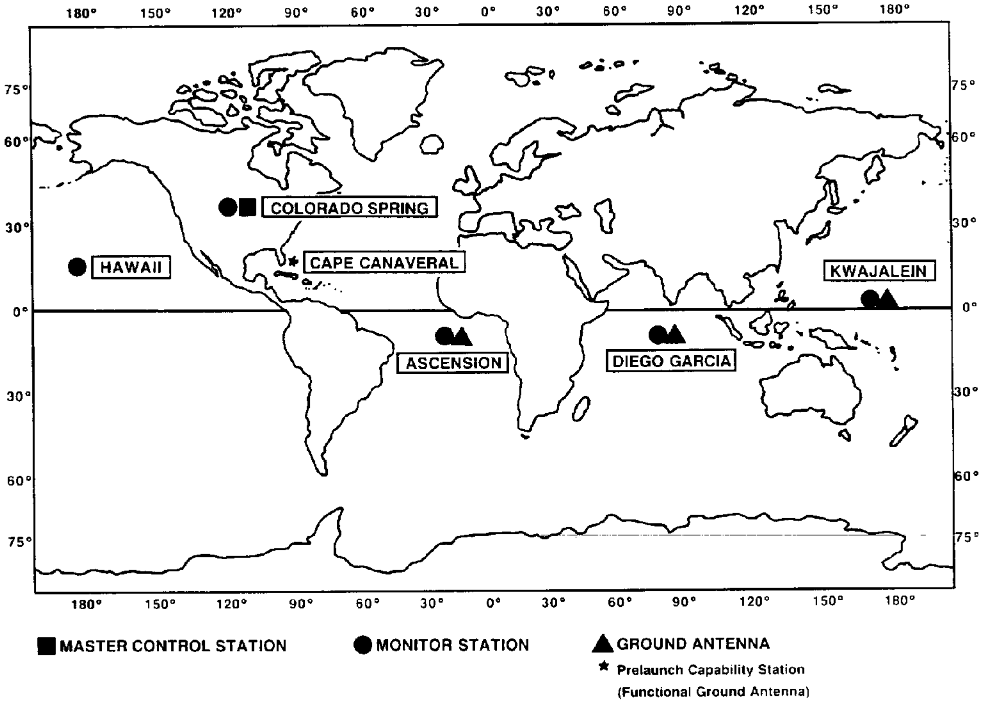
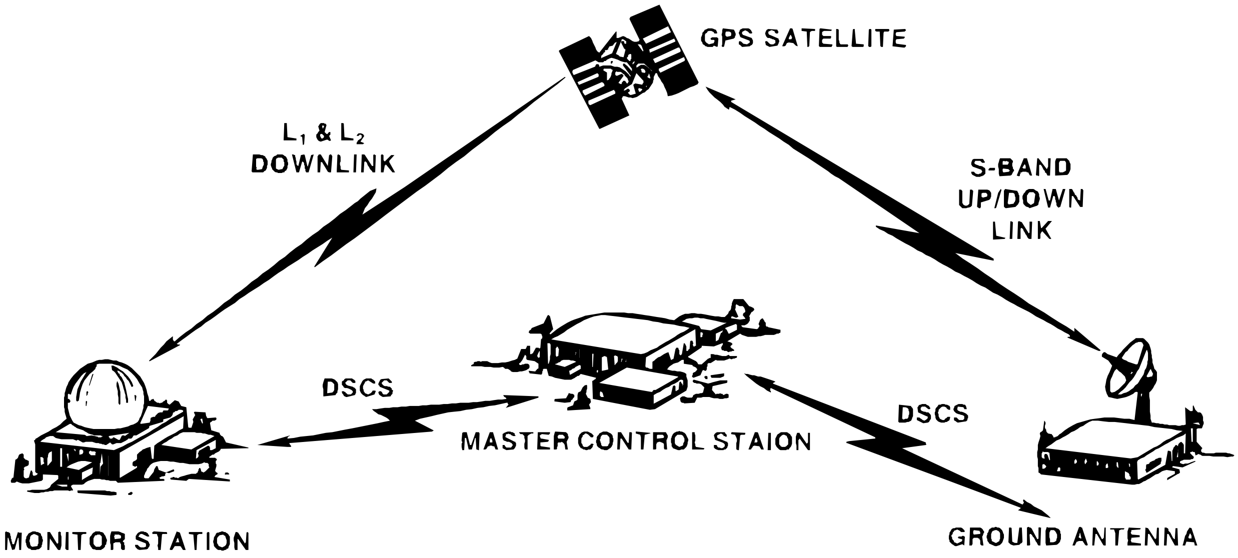


Figure 1-3. GPS Control Segment Locations

The MCS is the central processing facility for the Control Segment and is responsible for monitoring and managing the satellite constellation. The MCS functions include control of satellite station-keeping maneuvers, reconfiguration of redundant satellite equipment, regularly updating the navigation messages transmitted by the satellites, and various other satellite health monitoring and maintenance activities. The monitor stations passively track all GPS satellites in view, collecting ranging data from each satellite. This information is transmitted to the MCS where the satellite ephemeris and clock parameters are estimated and predicted. The MCS uses the ground antennas to periodically upload the ephemeris and clock data to each satellite for retransmission in the navigation message. Communications between the MCS the MS and GA are typically accomplished via the U.S. Defense Satellite Communication System (DSCS). The navigation message update function is graphically depicted in Figure 1-4.



*DSCS - Defense Satellite Communication System

Figure 1-4. Monitor Station and Ground Antenna

The PCS primarily operates under control of the MCS to support prelaunch compatibility testing of GPS satellites via a cable interface. The PCS also includes an RF transmit/receive capability that can serve as a Control Segment ground antenna, if necessary. The U.S. Air Force Satellite Control Network (AFSCN) consists of a multipurpose worldwide network of ground- and space-based satellite control facilities. Various AFSCN resources are available to support GPS but are not dedicated exclusively to GPS.

1.2.3 User Segment

The User Segment consists of receivers specifically designed to receive, decode, and process the GPS satellite signals. Receivers can be stand-alone, integrated with or embedded into other systems. GPS receivers can vary significantly in design and function, depending on their application for navigation, accurate positioning, time transfer, surveying and attitude reference. Chapter 2 provides a general description of GPS receiver types and intended applications.

1.3 GPS SERVICES

Two levels of service are provided by the GPS, the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS).

1.3.1 Precise Positioning Service

The PPS is an accurate positioning velocity and timing service which is available only to authorized users. The PPS is primarily intended for military purposes. Authorization to use the PPS is determined by the U.S. Department of Defense (DoD), based on internal U.S. defense requirements or international defense commitments. Authorized users of the PPS include U.S.

military users, NATO military users, and other selected military and civilian users such as the Australian Defense Forces and the U.S. Defense Mapping Agency. The PPS is specified to provide 16 metres Spherical Error Probable (SEP) (3-D, 50%) positioning accuracy and 100 nanosecond (one sigma) Universal Coordinated Time (UTC) time transfer accuracy to authorized users. This is approximately equal to 37 metres (3-D, 95%) and 197 nanoseconds (95%) under typical system operating conditions. PPS receivers can achieve 0.2 metres per second 3-D velocity accuracy, but this is somewhat dependent on receiver design.

Access to the PPS is controlled by two features using cryptographic techniques, Selective Availability (SA) and Anti-Spoofing (A-S). SA is used to reduce GPS position, velocity, and time accuracy to the unauthorized users. SA operates by introducing pseudorandom errors into the satellite signals. The A-S feature is activated on all satellites to negate potential spoofing of the ranging signals. The technique encrypts the P-code into the Y-code. Users should note the C/A code is not protected against spoofing.

Encryption keys and techniques are provided to PPS users which allow them to remove the effects of SA and A-S and thereby attain the maximum accuracy of GPS. PPS receivers that have not been loaded with a valid cryptographic key will have the performance of an SPS receiver.

PPS receivers can use either the P(Y)-code or C/A-code or both. Maximum GPS accuracy is obtained using the P(Y)-code on both L1 and L2. P(Y)-code capable receivers commonly use the C/A-code to initially acquire GPS satellites.

1.3.2 Standard Positioning Service

The SPS is a less accurate positioning and timing service which is available to all GPS users. In peacetime, the level of SA is controlled to provide 100 metre (95%) horizontal accuracy which is approximately equal to 156 metres 3D (95%). SPS receivers can achieve approximately 337 nanosecond (95%) UTC time transfer accuracy. System accuracy degradations can be increased if it is necessary to do so, for example, to deny accuracy to a potential enemy in time of crisis or war. Only the President of the United States, acting through the U.S. National Command Authority, has the authority to change the level of SA to other than peacetime levels.

The SPS is primarily intended for civilian purposes, although it has potential peacetime military use. Refer to "Technical Characteristics of the Navstar GPS" for additional details regarding SPS performance characteristics.

1.4 GPS THEORY OF OPERATION

The ranging codes broadcast by the satellites enable a GPS receiver to measure the transit time of the signals and thereby determine the range between a satellite and the user. The navigation message provides data to calculate the position of each satellite at the time of signal transmission. From this information, the user position coordinates and the user clock offset are calculated using simultaneous equations. Four satellites are normally required to be simultaneously "in view" of the receiver for 3-D positioning purposes. The following paragraphs give a description of the GPS satellite signals and GPS receiver operation.

1.4.1 GPS Satellite Signals

1.4.1.1 C/A-Code

The C/A-code consists of a 1023 bit pseudorandom noise (PRN) code with a clock rate of 1.023 MHz which repeats every 1 millisecond. The short length of the C/A-code sequence is designed to enable a receiver to rapidly acquire the satellite signals which helps the receiver transition to the longer P-code. A different PRN is assigned to each GPS satellite and selected from a set of codes called Gold codes. The Gold codes are designed to minimize the probability that a receiver will mistake one code for another (minimize the cross-correlation). The C/A-code is transmitted only on L1. The C/A-code is not encrypted and is therefore available to all users of GPS.

1.4.1.2 P(Y)-Code

The P-code is a 10.23 MHz PRN code sequence that is 267 days in length. Each of the GPS satellites is assigned a unique seven-day segment of this code that restarts every Saturday/Sunday midnight GPS time (GPS time is a continuous time scale maintained within 1 microsecond of UTC, plus or minus a whole number of leap seconds). The P-code is normally encrypted into the Y-code to protect the user from spoofing. Since the satellites have the capability to transmit either the P- or Y-code, it is often referred to as the P(Y)-code. The P(Y)-code is transmitted by each satellite on both L1 and L2. On L1, the P(Y)-code is 90 degrees out of carrier phase with the C/A-code.

1.4.1.3 Navigation Message

A 50 Hz navigation message is superimposed on both the P(Y) code and the C/A-code. The navigation message includes data unique to the transmitting satellite and data common to all satellites. The data contains the time of transmission of the message, a Hand Over Word (HOW) for the transition from C/A-code to P(Y)-code tracking, clock correction, ephemeris, and health data for the transmitting satellite, almanac and health data for all satellites, coefficients for the ionospheric delay model, and coefficients to calculate UTC.

The navigation message consists of 25 frames of data, each frame consisting of 1,500 bits. Each frame is divided into 5 subframes of 300 bits each (see Figure 1-5). At the 50 Hz transmission rate, it takes 6 seconds to receive a subframe, 30 seconds to receive one data frame, and 12.5 minutes to receive all 25 frames. Subframes 1, 2, and 3 have the same data format for all 25 frames. This allows the receiver to obtain critical satellite-specific data within 30 seconds. Subframe 1 contains the clock correction for the transmitting satellite, as well as parameters describing the accuracy and health of the broadcast signal. Subframes 2 and 3 contain ephemeris (precise orbital) parameters used to compute the location of the satellite for the positioning equations.

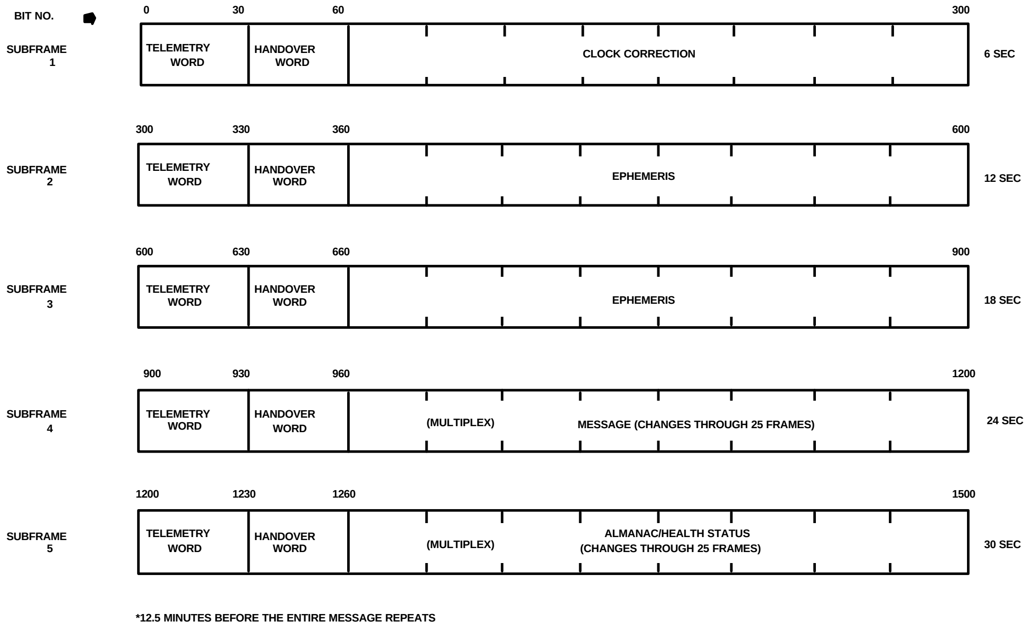


Figure 1-5. The Navigation Message

Subframes 4 and 5 have data which cycle through the 25 data frames. They contain data which is common to all satellites and less critical for a receiver to acquire quickly. Subframes 4 and 5 contain almanac (coarse orbital) data and low-precision clock corrections, simplified health and configuration status for every satellite, user text messages, and the coefficients for the ionospheric model and UTC calculation. A comprehensive description of the navigation message is provided in "Technical Characteristics of the Navstar GPS", together with the standard algorithms needed to use the data correctly.

1.4.1.4 Satellite Signal Modulation

The L1 carrier is BPSK modulated by both the C/A- and P(Y)-codes plus the navigation message superimposed on both codes. The L2 carrier is BPSK modulated by the P(Y)-code superimposed with the navigation message. The BPSK technique reverses the carrier phase when the modulating code changes from logic 0 to 1 or 1 to 0. On L1, the C/A-code is 90 degrees out of phase with the P(Y)-code. Figure 1-6 shows this modulation scheme in schematic form.

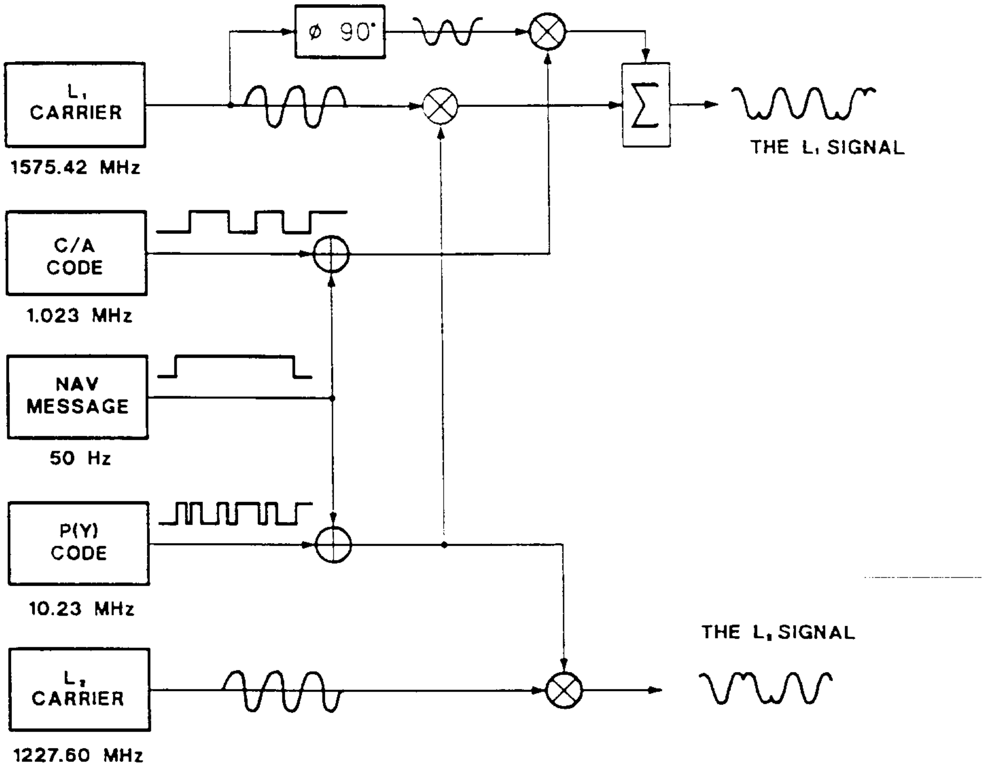


Figure 1-6. Satellite Signal Modulation

The BPSK modulation spreads the RF signals by the code bandwidth. The result is a symmetrical spreading of the signal around the L1 and L2 carriers. The C/A-code spreads the L1 signal power over a 2.046 MHz bandwidth centered at 1575.42 MHz. The P(Y)-code spreads the L1 and L2 signal powers over a 20.46 MHz bandwidth centered about 1575.42 MHz on L1 and 1227.6 MHz on L2. Figure 1-7 shows the L1 and L2 signal spectrum as it appears at the 0 dB gain receiver antenna at the Earth's surface. The C/A-code component of L1 signal has a power of -160 dBW (decibels with respect to one watt), the L1 P(Y)-code signal has a power of -163 dBW, and the L2 P(Y)-code signal has a power of -166 dBW.

1.4.2 GPS Receiver Operation

In order for the GPS receiver to calculate a PVT solution, it must:

Search for a PRN C/A code lock
C/A code track, carrier track
Obtain bit synchronization with the navigation message
Obtain frame synchronization, ie obtain HOW and Z count
Decode GUV or CVw
Remove SA
Transition to P(Y)-code, -code lock, -carrier lock
Data lock on P(Y) code
Search, acquire and track 2nd to 4th SVs, up to all in view

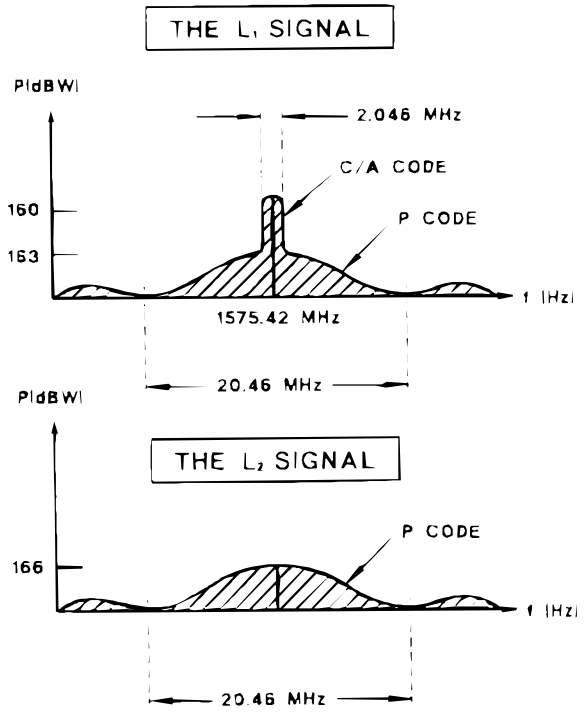


Figure 1-7. GPS Signal Frequency Spectrum

Take range and range rate measurements
Solve for range equations
P(Y) code measurements L2 to remove ionospheric delays and refine navigation solution.

Details of the operations are expanded below.

1.4.2.1 Satellite Selection

A typical satellite tracking sequence begins with the receiver determining which satellites are visible for it to track. If the receiver can immediately determine satellite visibility, the receiver will target a satellite to track and begin the acquisition process. Satellite visibility is determined based on the GPS satellite almanac and the initial receiver estimate (or user input) of time and position. If the receiver does not have the almanac and position information stored, the receiver enters a "search the sky" operation that systematically searches the PRN codes until lock is obtained on one of the satellites in view. Once one satellite is successfully tracked, the receiver can demodulate the navigation message data stream and acquire the current almanac as well as the health status of all the other satellites in the constellation.

Depending on its architecture, a receiver selects either a "best" subset of the visible satellites to track or uses all healthy satellites in view to determine an "all-in-view" PVT solution. The all-in-view solution is usually more accurate than a four satellite solution although it requires a more complex receiver and receiver processing. The all-in-view solution is also more robust, since the temporary loss of a satellite signal (for example due to a physical obstruction near the receiver) does not disrupt the flow of PVT data while the receiver attempts to reacquire the lost signal. Many receivers will track more than four satellites, but less than all-in-view, as a compromise between complexity, accuracy, and robustness. Receivers that select a "best" subset do so based on geometry, estimated accuracy, or integrity. More detailed discussion of specific satellite selection criteria is provided in Chapter 6.

1.4.2.2 Satellite Signal Acquisition

The satellite signal power at or near the earth's surface is less than the receivers thermal (natural) noise level, due to the spread spectrum modulation of the signal, orbital height and transmitting power of the satellite. To extract the satellite signal the receiver uses code correlation techniques. An internal replica of the incoming signal is generated and aligned with the received satellite signal. The receiver shifts the replica code to match the incoming code from the satellite. When the codes match, the satellite signal is compressed back into the original carrier frequency band. This process is illustrated in Figure 1-8.

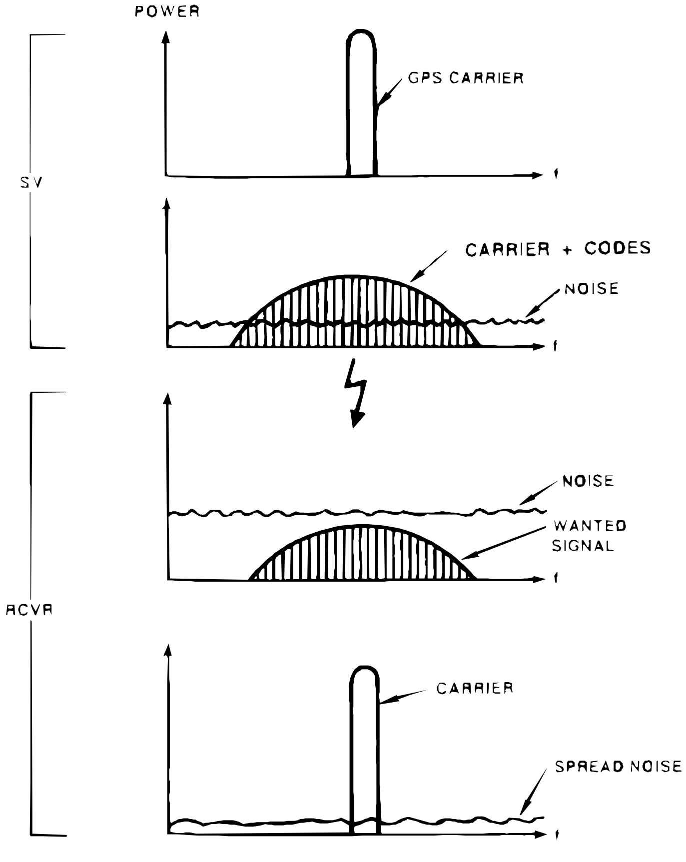


Figure 1-8. Spread Spectrum Generation and Reconstruction

The delay in the receiver's code is a measure of the transit time of the signals between the satellite and the receiver's antenna and hence, the range between the satellite position and receiver position. This measurement is called a pseudorange measurement, rather than a range measurement, because the receiver's clock bias has not been removed.

Receivers typically use phase-locked-loop techniques to synchronize the receiver's internally generated code and carrier with the received satellite signal. A code tracking loop is used to track the C/A- and P-code signals while a carrier tracking loop is used to track the carrier frequency. The two tracking loops work together in an interactive process, aiding each other, in order to acquire and track the satellite signals. A generic GPS receiver tracking system is illustrated in Figure 1-9.

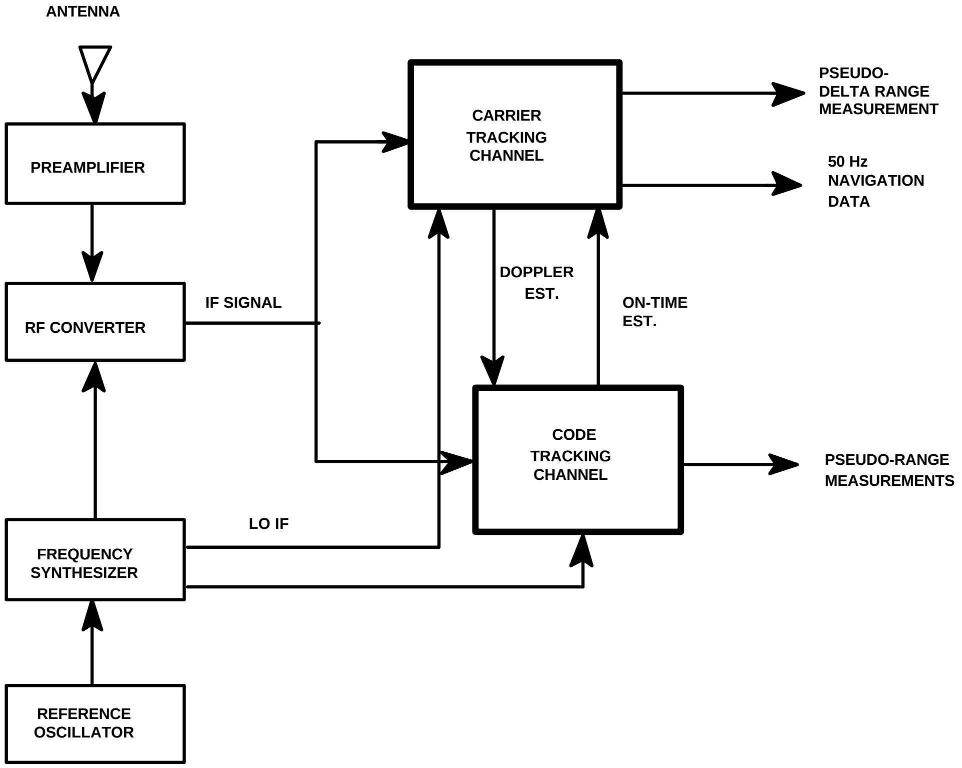


Figure 1-9. Generic GPS Receiver Tracking System

1.4.2.3 Down Conversion

The received RF signal is converted, usually through two intermediate frequencies (IF), down to a frequency near the code baseband, that can be sampled by an analogue to digital (A/D) converter. Inphase and quadrature digital samples are taken to preserve the phase information in the received signal. The samples are usually two bits to reduce conversion losses. The sampling rate must be higher than the code chipping rate for a non return to zero code, that is, greater than 10.23 MHz for the P(Y)-code. To ensure the phase of the received signal is maintained, all local oscillators are derived from, and phased locked through, a series of synthesizers derived from the receiver's master oscillator. Following the A/D conversion there is a final phase rotation circuit that enables the doppler in the satellite signal to be precisely tracked.

1.4.2.4 Code Tracking

The code tracking loop is used to make pseudorange measurements between the GPS satellites and the GPS receiver. The receiver's code tracking loop generates a replica of the C/A-code of the targeted satellite. The estimated doppler is removed by the phase rotation circuit prior to the correlator.

In order to align the received signal with the internally generated replica, the internally generated code is systematically slewed past the received signal. Typically the output of the correlator is integrated over 1 to 10 ms. If correlation is not detected the phase of the internally generated code is advanced by one chip. If correlation is not detected after the whole code has been searched the doppler is adjusted and the process repeated until correlation is achieved. Code synchronization is initially maintained by also correlating the received signal with half chip early and late codes. A simple feedback system keeps the prompt ("on time") code correctly positioned. To extract the carrier which is still modulated by the navigation message, the prompt code is subtracted from the incoming signal. The delay that the receiver must add to the replica code to achieve synchronization (correlation), multiplied by the speed of light, is the pseudorange measurement. Once the carrier is reconstructed, the center frequency of the replica code is adjusted using Doppler measurements from the carrier tracking loop to achieve a precise frequency lock to the incoming signal, thereby allowing more precise pseudorange measurements. The bandwidth of the code tracking loop is typically 0.1 Hz, which implies that independent measurements are available at approximately 10 s intervals.

1.4.2.5 Carrier Tracking and Data Detection

The receiver tracks the satellite carrier by adjusting the frequency synthesizers to produce a stationary phase at the output of the code tracking loop. The inphase and quadrature components are used to calculate the carrier's phase and doppler. A data bit is detected by a sudden change in the phase of the detected signal. The bandwidth of the carrier tracking loop is typically 6 Hz for a military airborne receiver, resulting in independent measurements being available every 150 ms.

Doppler is measured to provide an estimate of the relative velocity between the receiver and the satellite. These measurements are typically termed pseudorange rate measurements or they can be integrated over regular time intervals to produce deltarange measurements.

The receiver uses the doppler measurements from four (or more) satellites to determine the receiver velocity (in three dimensions) plus the receiver's master oscillator frequency bias. The deltarange measurements of the carrier tracking loop are also used to aid the code tracking loop to ensure code tracking is maintained during dynamic maneuvers where the simple code tracking system would be unable to maintain lock.

1.4.2.6 Data Demodulation

Once the carrier tracking loop is locked, the 50 Hz navigation data message can be read. Each subframe of the navigation message begins with a preamble contained in the Telemetry Word, enabling the receiver to detect the beginning of each subframe. Each subframe is identified by bits contained in the Handover Word (HOW), enabling the receiver to properly decode the subframe data.

1.4.2.7 P(Y)-Code Signal Acquisition

The one millisecond C/A-code length permits a relatively narrow search window for code correlation even if the receiver must "search the sky" to find the first satellite. However the week long P(Y)-code sequence at 10.23 MHz does not allow the same technique to be used. Precise time must be known by the receiver in order to start the code generator within a few hundred chips of the correlation point of the incoming signal. The HOW contained in the GPS navigation message provides satellite time and hence the P(Y)-code phase information. A P(Y)-code receiver may attempt to acquire the P(Y)-code directly, without first acquiring the C/A-code, if it has accurate knowledge of position, time and satellite ephemeris from a recent navigation solution. External aiding and/or an enhanced acquisition technique are usually required to perform direct P(Y)-code acquisition.

1.4.2.8 PVT Calculations

When the receiver has collected pseudorange measurements, deltarange measurements, and navigation data from four (or more) satellites, it calculates the navigation solution, PVT. Each navigation data message contains precise orbital (ephemeris) parameters for the transmitting satellite, enabling a receiver to calculate the position of each satellite at the time the signals were transmitted. The ephemeris data is normally valid and can be used for precise navigation for a period of four hours following issue of a new data set by the satellite. New ephemeris data is transmitted by the satellites every two hours.

As illustrated in Figure 1-10, the receiver solves a minimum of four simultaneous pseudorange equations, with the receiver (3-D) position and clock offset as the four unknown variables. Each equation is an expression of the principle that the true range (the difference between the pseudorange and the receiver clock offset) is equal to the distance between the known satellite position and the unknown receiver position. This principle is expressed below mathematically using the same notation as Figure 1-10.

$$R - C_B = c\Delta t - C_B = \sqrt{(X - U_X)^2 + (Y - U_Y)^2 + (Z - U_Z)^2}$$

These are simplified versions of the equations actually used by GPS receivers. A receiver also obtains corrections derived from the navigation messages which it applies to the pseudoranges. These include corrections for the satellite clock offset, relativistic effects, ionospheric signal propagation delays. Dual frequency receivers can measure the delay between the L1 and L2 P(Y)-codes, if available, to calculate an ionospheric correction. Single frequency (either C/A-or P(Y)-code) receivers use parameters transmitted in the navigation message to be used in an ionospheric model. The receiver (3-D) velocity and frequency offset are calculated using similar equations, using deltaranges instead of pseudoranges.

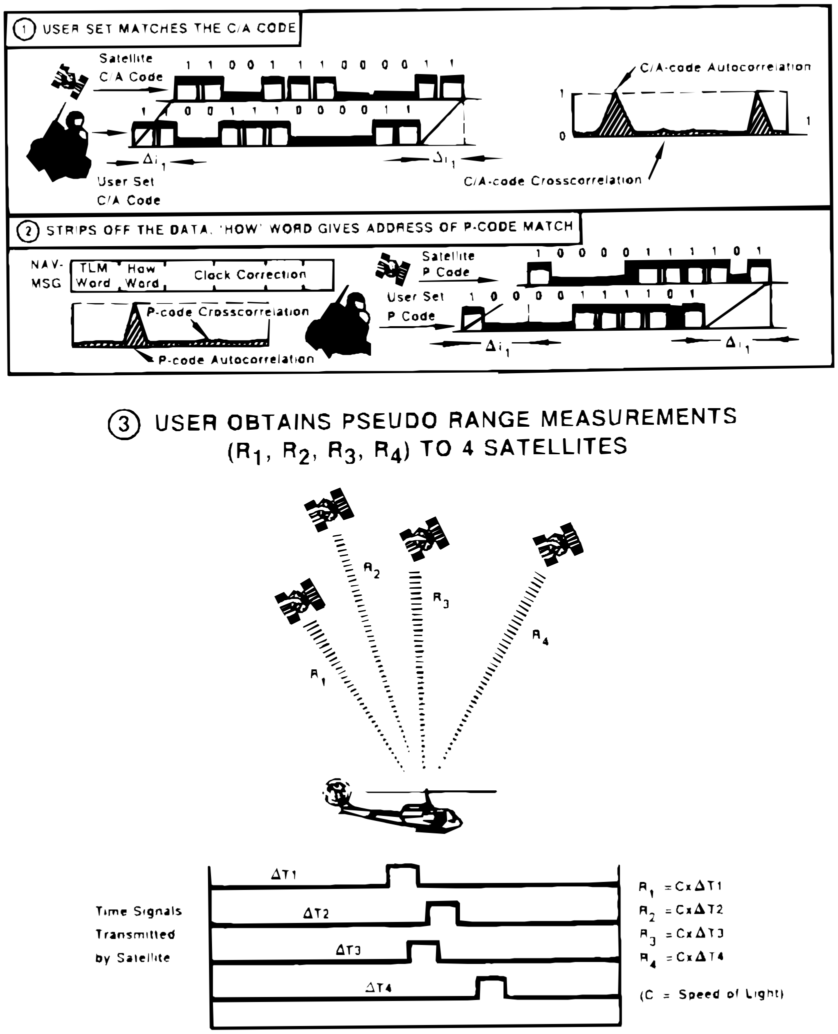
The PVT calculations described here result in a series of individual point solutions. For receivers that are required to provide a navigation solution under dynamic conditions a smoothed or filtered solution that is less sensitive to measurement noise is employed. One of the most common types of filters used in GPS receivers is the Kalman filter. Kalman filtering is described in detail in Chapter 9.

The rate at which GPS receivers calculate the PVT solution is governed by their application. For flight control applications a 10 Hz rate is required whereas in handheld equipment a fix may only be required once every 4 to 5 seconds or at even longer intervals. A 1 Hz rate is typical for many equipments. In this scenario pseudorange measurements are typically only made every 4 to 5 seconds; pseudorange rate measurements are made more frequently and can be used to propagate the filter solution between updates. If a Kalman filter is used the measurements may be incorporated independently into the filter removing the requirement for symmetrical measurements from all channels. The filter also allows the solution to be extrapolated if measurements are interrupted, or data is available from other navigation sensors.

A minimum of four satellites are normally required to be simultaneously "in view" of the receiver, thus providing four pseudorange and four deltarange measurements. Treating the user clock errors as unknowns enable most receivers to be built with an inexpensive crystal oscillator rather than an expensive precision oscillator or atomic clock. Less than four satellites can be used by a receiver if time or altitude are precisely known or if these parameters are available from an external source.

GPS receivers perform initial position and velocity calculations using an earth-centered earth-fixed (ECEF) coordinate system. Results may be converted to an earth model (geoid) defined by the World Geodetic System 1984 (WGS 84). WGS 84 provides a worldwide common grid system that may be translated into local coordinate systems or map datums. (Local map datums are a best fit to the local shape of the earth and not valid worldwide.) For more details regarding WGS 84, refer to Annex B. For more details regarding how a receiver uses WGS 84, refer to "Technical Characteristics of the Navstar GPS".

For navigation purposes, it is usually necessary for a GPS receiver to output positions in terms of magnetic North rather than true North as defined by WGS 84. For details regarding how the receiver calculates the magnetic variation from true North, refer to "Technical Characteristics of the Navstar GPS".



④ USER SET PERFORMS THE NAV SOLUTION FOR POSITION

PSEUDO RANGES:

$\textcircled{R_1} = C\Delta t_1$

$\textcircled{R_2} = C\Delta t_2$

$\textcircled{R_3} = C\Delta t_3$

$\textcircled{R_4} = C\Delta t_4$

POSITION EQUATIONS:

$(X_1 - \textcircled{U_X})^2 + (Y_1 - \textcircled{U_Y})^2 + (Z_1 - \textcircled{U_Z})^2 = (R_1 - \textcircled{C_B})^2$

$(X_2 - \textcircled{U_X})^2 + (Y_2 - \textcircled{U_Y})^2 + (Z_2 - \textcircled{U_Z})^2 = (R_2 - \textcircled{C_B})^2$

$(X_3 - \textcircled{U_X})^2 + (Y_3 - \textcircled{U_Y})^2 + (Z_3 - \textcircled{U_Z})^2 = (R_3 - \textcircled{C_B})^2$

$(X_4 - \textcircled{U_X})^2 + (Y_4 - \textcircled{U_Y})^2 + (Z_4 - \textcircled{U_Z})^2 = (R_4 - \textcircled{C_B})^2$

R_i = PSEUDO RANGE (i = 1,2,3,4)

- PSEUDO RANGE INCLUDES ACTUAL DISTANCE BETWEEN SATELLITE AND USER PLUS SV CLOCK BIAS, USER CLOCK BIAS, ATMOSPHERIC DELAYS, AND RECEIVER NOISE
- SV CLOCK BIAS AND ATMOSPHERIC DELAYS ARE COMPENSATED FOR BY INCORPORATION OF DETERMINISTIC CORRECTIONS PRIOR TO INCLUSION INTO NAV SOLUTION

X_i, Y_i, Z_i = SATELLITE POSITION (i = 1, 2, 3, 4)

- SATELLITE POSITION BRAODCAST IN NAVIGATION 50 Hz MESSAGE

RECEIVER SOLVES FOR:

- U_x, U_y, U_z = USER POSITION
- C_B = USER CLOCK BIAS

Figure 1-10. GPS Receiver Theory of Operation

1.4.2.9 Degraded Operation and Aiding

During periods of high levels of jamming, the receiver may not be able to maintain both code and carrier tracking. The receiver normally has the capability to maintain code tracking even when carrier tracking is no longer possible. If only code tracking is available, the receiver will slew the locally generated carrier and code signals based on predicted rather than measured Doppler shifts. These predictions are performed by the receiver processor, which may have additional PVT information available from an external aiding source. See Chapter 7 for additional discussion of GPS receiver aiding.

1.5 PROGRAM MANAGEMENT

1.5.1 System Development and Management

The United States Air Force (USAF), Air Force Materiel Command, Space and Missile Center (SMC), Navstar GPS Joint Program Office (JPO) has total system responsibility for the GPS. The SMC and GPS JPO are located at the Los Angeles Air Force Base (AFB) in Los Angeles, California. The GPS JPO is manned by personnel from the USAF, US Navy, US Army, US Marine Corps, US Department of Transportation, US Defense Mapping Agency. NATO Nations and Australia may have representatives stationed at the JPO. The GPS JPO was responsible for development of the Control and Space Segments and is responsible for acquisition of replenishment satellites and common user equipment (UE) for all military services. The GPS JPO also provides technical support, security guidance, technical specification development, interface control documents, and implementation guidelines. NATO and other allied Nations have established Memoranda of Understanding with the United States which provides access to PPS, interchange of technical information, and the ability to purchase or locally manufacture PPS GPS UE.

The GPS JPO is supported by the Launch Vehicle System Program Office (SPO) and the Network SPO, also located at the SMC. The Launch Vehicle SPO provides the expendable boosters used to launch the Navstar satellites. The Network SPO is responsible for continuing development of the multi-use AFSCN. GPS JPO program management operations are also supported by the User Equipment Support Program Manager located at the Warner-Robbins Air Logistics Center in Warner Robbins, Georgia and by Detachment 25 (from the Sacramento Air Logistics Center) located at Colorado Springs, Colorado.

1.5.2 System Requirements, Planning, and Operations

The USAF Space Command (AFSPC) is responsible for GPS requirements, planning, and operations. Headquarters of the AFSPC and the requirements and planning functions are located at Peterson AFB in Colorado Springs, Colorado. Various agencies within the USAF Space Command (AFSPC) operate and maintain the Control Segment, prepare and launch the Navstar satellites, manage the operational constellation, and interface with the GPS user community. Elements of the AFSPC Fiftieth Space Wing (50SPW) are responsible for launch, early orbit support, and continued day-to-day operations of the GPS satellites.

The First Space Operations Squadron (1SOPS) of the 50SPW, located at Falcon AFB in Colorado Springs, Colorado, provides launch and early-orbit support for the GPS satellites. The early orbit support includes control of the Navstar satellites to deploy solar arrays, perform stabilization maneuvers, and complete other procedures to make the satellites ready for service. The 1SOPS can also provide backup capability for critical day-to-day commanding procedures if necessary. When a satellite is ready for service, command is transferred to the Second Space Operations Squadron (2SOPS) of the 50SPW for payload turn-on and continued operations. The 2SOPS has responsibility for day-to-day operations and overall constellation management. The 2SOPS is also located at Falcon AFB.

The Forty-Fifth Space Wing (45SPW) of the AFSPC is responsible for management of Navstar pre-launch operations, including receiving of the satellites, storage on the ground if necessary, mating to the launch vehicle, and integration and compatibility testing. The 45SPW is located at Cape Canaveral Air Force Station, Florida, which is the launch site for the GPS satellites.

1.6 GPS PROGRAM HISTORY

1.6.1 Pre-Concept Validation (1960s-1972)

Since the early 1960s various U.S. agencies have had navigation satellite programs. The John Hopkins' Applied Research Laboratory sponsored the TRANSIT program and the U.S. Navy (USN) sponsored the TIMATION (TIMe navigATION) program. TIMATION was a program to advance the state of the art for two-dimensional (latitude and longitude) navigation. TRANSIT became operational in 1964 and is currently providing navigation service to low dynamic vehicles such as ships. It is scheduled to be phased out in 1996. The USAF conducted concept studies to assess a three-dimensional (latitude, longitude, and altitude) navigation system called 621B.

1.6.2 Phase I - Concept Validation (1973-1979)

A memorandum issued by the US Deputy Secretary of Defense on 17 April 1973 designated the USAF as the executive service to consolidate the TIMATION and 621B concepts into a comprehensive all-weather navigation system named Navstar GPS. The Navstar GPS JPO was established on 1 July 1973.

Two experimental Navigation Technology Satellites (NTS) were built and launched to support concept validation of the GPS. The first true GPS signals from space came from NTS-2. NTS-2 was launched on an Atlas booster from Vandenberg AFB in June 1977 but malfunctioned after only 8 months. The first Navstar GPS Block I (research and development) satellite was launched in February 1978. A total of 11 Block I satellites were launched between 1978 and 1985. All of the Block I satellites were launched from Vandenberg AFB using the Atlas booster. Block I satellites did not incorporate SA or A-S features. As of June 1995 only one Block I satellite remained operational. Table 1-1 contains the launch dates and status (as of June 1995) of the NTS and Block I satellites.

Table 1-1. NTS and Block I Satellite Launch Dates and Status

Navstar Number	Space Vehicle No. (SVN)	PRN Code Number	Launch Date	Status (June 95)
NTS-1	-	-	14 Jul 74	Deactivated
NTS-2	-	-	23 Jun 77	Deactivated Jan 78
I-1	1	-	22 Feb 78	Deactivated 25 Jan 80
I-2	2	-	12 May 78	Deactivated 30 Aug 80
I-3	3	-	06 Oct 78	Deactivated 19 Apr 92
I-4	4	-	11 Dec 78	Deactivated 06 Sep 86
I-5	5	-	09 Feb 80	Deactivated 28 Nov 83
I-6	6	-	26 Apr 80	Deactivated 05 Mar 91
I-7	7	-	18 Dec 81	Launch Failure
I-8	8	-	14 Jul 83	Deactivated 4 May 93
I-9	9	-	13 Jun 84	Deactivated 28 Feb 94
I-10	10	12	08 Sep 84	Operational
I-11	11	-	09 Oct 85	Deactivated 14 Apr 94

The first Control Segment consisted of a control station, ground antenna, and monitor station located at Vandenberg AFB in California, supported by additional monitor stations located at Elmendorf AFB in Alaska, Anderson AFB in Guam, and the Naval Communications Station in Hawaii. This Phase I Control Segment was designated the Initial Control System (ICS).

The first user equipment (UE) testing began at Yuma Proving Ground (YPG) in March 1977 using ground transmitters to simulate the GPS satellites. As the Block I satellites were launched, a combination of satellites and ground transmitters were used for testing until December 1978, when four satellites were available to provide limited 3-D navigation capability. Shipborne UE was tested off the coast of California starting in October 1978 when three GPS satellites were available for two-dimensional (2-D) navigation.

1.6.3 Phase II - Full Scale Development (1979-1985)

In September 1980, a contract was awarded to upgrade and operate the ICS, as well as develop an Operational Control System (OCS). The ICS upgrades ensured continued support to the UE test team while the OCS was being developed. OCS equipment was delivered to Vandenberg AFB in May 1985. In October 1985, after installation and initial testing, the OCS conducted dual operations with the ICS. The OCS equipment was moved from Vandenberg to its permanent site at Falcon AFB by the end of 1985. In December 1980, the contractor was selected to provide 28 Block II (operational) Navstar GPS satellites. Development of the satellites continued throughout Phase II.

Phase II for the User Segment was divided into two parts. In Phase IIA, starting in July 1979, four contractors were selected to conduct performance analyses and preliminary design of UE. In Phase IIB, starting in 1982, two of the four contractors were selected to continue UE development. Phase IIB included design refinement, fabrication of prototypes, qualification testing, and extensive field testing of the UE. The UE was tested at YPG and at sea. Testing at sea was conducted by Naval Ocean Systems Center located in San Diego, California.

1.6.4 Phase III - Production and Deployment (1986 to Present)

1.6.4.1 Space Segment (1986 to Present)

The Block II satellites were originally designed to be launched aboard the Space Transportation System (Space Shuttle). Following an accident with the Space Shuttle Challenger in 1986, the Block II satellite-to-launch-vehicle interface was modified to enable launch aboard the Delta II booster. The first Block II satellite was launched on 14 February 1989. The combined constellation of Block I and Block II satellites achieved worldwide two-dimensional positioning capability in June 1991. Worldwide 3-D capability was achieved in 1993. The Initial Operational Capability (IOC) was declared on 8 December 1993. A full 24-satellite constellation of Block II satellites was achieved in April 1994. The military Full Operational Capability is planned for 1995. The remaining Block II satellites will be launched on demand. Table 1-2 is a summary of the Block II launch dates and status.

In June of 1989 a contract was awarded for 20 GPS replenishment satellites, designated Block IIR. The Block IIR satellites will have the capability to autonomously generate their own navigation messages. The Block IIR production schedule may allow a first launch as early as August 1996. In 1994, efforts were begun by the GPS JPO to procure additional Navstar satellites to sustain the GPS satellite constellation past the year 2000. These satellites are designated Block IIF (Follow-On). The contract to provide the Block IIF satellites is planned for November 1995. The planned production schedule supports a first launch in the year 2001.

In 1994 the GPS JPO also began studies for an Augmented GPS (AGPS). The AGPS concept is to enhance the availability, accuracy and integrity of the GPS system using up to six geostationary AGPS satellites. The satellites would broadcast integrity information and range corrections for all GPS satellites via GPS-like ranging signals.

Table 1-2. Block II Satellite Launch Dates and Status

Navstar Number	Space Vehicle No. (SVN)	PRN Code Number	Launch Date	Status (June 95)
II-1	14	14	14 Feb 89	Operational
II-2	13	2	10 Jun 89	Operational
II-3	16	16	17 Aug 89	Operational
II-4	19	19	21 Oct 89	Operational
II-5	17	17	11 Dec 89	Operational
II-6	18	18	24 Jan 90	Operational
II-7	20	20	25 Mar 90	Operational
II-8	21	21	02 Aug 90	Operational
II-9	15	15	01 Oct 90	Operational
II-10	23	23	26 Nov 90	Operational
II-11	24	24	03 Jul 91	Operational
II-12	25	25	23 Feb 92	Operational
II-13	28	28	09 Apr 92	Operational
II-14	26	26	07 Jul 92	Operational
II-15	27	27	09 Sep 92	Operational
II-16	32	01	22 Nov 92	Operational
II-17	29	29	18 Dec 92	Operational
II-18	22	22	02 Feb 93	Operational
II-19	31	31	29 Mar 93	Operational
II-20	37	07	12 May 93	Operational
II-21	39	09	26 Jun 93	Operational
II-22	35	05	30 Aug 93	Operational
II-23	34	04	26 Oct 93	Operational
II-24	36	06	09 Mar 94	Operational
II-25	TBD	TBD	TBD	To Be Launched
II-26	TBD	TBD	TBD	To Be Launched
II-27	TBD	TBD	TBD	To Be Launched
II-28	TBD	TBD	TBD	To Be Launched

1.6.4.2 Control Segment (1986 to Present)

The GPS OCS achieved Full Operational Capability (FOC) in December 1986. In March 1986, the ICS at Vandenberg AFB was deactivated. In December 1989, verification of the OCS operational capability was completed by the USAF Operational Test and Evaluation Center. Turnover of the OCS to AFSPC was accomplished in June 1990. Since then, Control Segment development activities have been limited to upgrades of the operational software and additions to the equipment and facilities. The OCS has been augmented with a transportable GA capability and Back-Up MCS capability.

1.6.4.3 User Segment (1986 to Present)

1.6.4.3.1 GPS JPO Activities

In April 1985, the contractor was selected for the Phase III production GPS UE. Low rate initial production of the UE was begun and the first set was delivered to the JPO in June 1988. In January 1992, full rate production of the UE was approved. The Phase III production UE includes the 5-channel Receiver 3A (R-2332/AR) for airborne use, the 5-channel Receiver 3S (R-2331/AR) for shipboard use, the 2-channel Receiver OH (R-2399/AR) and UH (R-2400/AR) for helicopter use, and the RPU-1 (R-2401/U) for manpack and ground vehicle use.

In 1989, a contract was awarded for 2-channel SPS C/A-code receivers to be used primarily for demonstration and training. These receivers are known as the Small Lightweight GPS Receiver (SLGR, AN/PSN-10). They are suitable for vehicle mounting or handheld use. In 1990, a large second purchase was made. Although originally intended for nontactical use, these receivers were used extensively in support of Operation Desert Shield and Operation Desert Storm.

In November 1990, a contract was awarded to develop a 5-channel 3/8 ATR (Air Transport Rack) size Miniature Airborne GPS Receiver (MAGR) for use in aircraft where space is severely limited. The contract to deliver operational models was awarded in April 1993 with the first delivery occurring in July 1994. Two versions of the MAGR have been produced. One version uses an RF interface directly from the antenna (R-2512/U) the other (R-2514/U) uses an IF (intermediate frequency) interface from an antenna electronics unit.

In February 1993, a contract was awarded to produce a hand-held PPS GPS receiver. Designated the Precision Lightweight GPS Receiver (PLGR, AN/PSN-11), it weighs less than 4 pounds, is self-contained as a handheld unit, and can be adapted for vehicle mounting. Delivery of the PLGR began in September 1993.

In the 1990s, the GPS JPO has continued to sponsor activities to improve the functions and performance of military GPS receivers. Activities are continuing that will improve anti-jamming performance of GPS antennas, antenna electronics units, and receiver signal processing. In 1994, procurement efforts were begun for a new Controlled Reception Pattern Antenna (CRPA). The new CRPA will be compatible with the form, fit, and function of the existing CRPA system procured by the JPO. Efforts are also underway that will allow Receiver Autonomous Integrity Monitoring (RAIM) to be implemented where enhanced GPS integrity or compatibility with civil aviation is desired. Other efforts are underway to add differential GPS (DGPS) to future military PPS receivers, to support new applications, such as precise positioning and aircraft precision approach. Additional programs that are underway or under consideration include a space-based GPS PPS receiver, a miniaturized PLGR, and a Survey GPS Receiver (SGR). Since 1993, the GPS JPO has been developing standards for a next generation PPS receiver module that can be embedded in other military systems. The JPO will not procure embedded GPS receivers (EGRs), but will provide technical support so that other military programs can procure the EGR as part of another system.

The JPO has released an EGR Guidelines document which contains EGR interface, design, and performance requirements, as well as general guidance material regarding the EGR and host system. The document also includes specific guidance for integrating GPS with inertial or Doppler navigation systems.

The JPO EGR effort is evolving into a standard for a GPS Receiver Applications Module (GRAM). The GRAM will consist of a family of standard EGR modules suitable for a variety of embedded applications. The GRAM standard will define several EGR physical configurations conforming to standard modular architectures, such as the Standard Electronic Module (SEM) and Versa Module Europa (VME). The standard will include specifications for advanced functions, such as local- and wide-area DGPS corrections and receiver-based integrity enhancements (RAIM). The standard will also accommodate the next-generation GPS receiver security module known as the Selective Availability/Anti-Spoofing Module (SAASM).

1.6.4.3.2 International Military UE and Commercial UE

Phase III of the GPS program has seen a tremendous expansion in the development and production of international military UE and commercial UE. Military UE is being produced by participating NATO nations including Canada, France, Germany, Italy, and the United Kingdom.

In addition, a wide variety of commercial SPS UE has been developed by manufacturers around the world for many different applications. Some of these receivers have been acquired by Military and Government authorities for nontactical applications such as surveying, test support, and training.

1.6.4.3.3 User Equipment Testing

Development Test and Evaluation (DT&E) and OT&E have included test and evaluation of:

a. Integrated GPS/host vehicle navigation system performance
b. Phase II and (early) Phase III deficiency corrections
c. Reliability and maintainability of the GPS UE
d. Operational effectiveness of the GPS UE against jamming and spoofing
e. The SA and A-S features

In addition to U.S.-sponsored test efforts, Australia, Canada, Denmark, Germany, the Netherlands, Norway, and the United Kingdom conducted an extensive Phase III International Test Program in cooperation with the JPO. These countries were joined by France, Greece, Portugal, Spain, and Turkey for a subsequent International Test Program that focused exclusively on the PLGR.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 2: TYPES OF GPS RECEIVERS AND THEIR INTENDED APPLICATIONS

2.1 GPS RECEIVER ARCHITECTURES

Modern military GPS receivers use predominantly a continuous satellite tracking architecture. However, some receivers use alternative architectures, either sequential or multiplex tracking to reduce hardware complexity.

2.1.1 Continuous Receivers

A continuous tracking receiver has five or more hardware channels to track four satellites simultaneously plus other channels to acquire new satellites. Due to their greater complexity, these receivers were traditionally the most expensive but offer the best performance and versatility. The multi-channel receiver uses the fifth channel to read the NAVigation (NAV) message of the next satellite to be used when the receiver changes the satellite selections. It also uses the fifth channel in conjunction with each of the other four channels to perform dual frequency measurements as well as differential channel delay measurements. Individual, dedicated tracking channels enable the receivers to maintain accuracy under high dynamics, provide the best anti-jamming (A-J) performance, and have the lowest TTFF. This type of receiver is best suited for high-dynamic vehicles such as fighter aircraft, vehicles requiring low TTFF such as submarines, plus any user requiring good A-J performance.

2.1.2 Sequential Receivers

A sequential GPS receiver tracks the necessary satellites by typically using one or two hardware channels. The set will track one satellite at a time, time tag the measurements and combine them when all four satellite pseudoranges have been measured. These receivers are among the least expensive available, but they cannot operate under high dynamics and have the slowest time-to-first-fix (TTFF) performance.

2.1.2.1 One-Channel Sequential Receivers

A 1-channel sequential receiver makes four pseudorange measurements on both the L1 and L2 frequencies in order to determine a position and compensate for ionospheric delay. The NAV message from each of the satellites must also be read to obtain ephemeris data. To determine an initial position, the receiver must perform the following operations, 1) C/A- code search for a SV, 2) C/A-code/carrier center, 3) data bit synchronization, 4) frame synchronization and Z-count, 5) HOW, 6) P-code carrier center, 7) data demodulation and 8) ionospheric measurements. Once these operations are complete for one SV, the receiver must perform them again for three other SVs. The four pseudorange measurements must be propagated to the same reference time before a navigation solution is generated. Any movement of the Host Vehicle (HV) during the time the receiver collects the four pseudoranges will reduce the accuracy of the position, velocity, and time calculations in the receiver. One-channel sequential receivers are limited to low-dynamic or stationary applications.

2.1.2.2 Two-Channel Sequential Receivers

Two-channel sequential receivers have been developed for use on medium-dynamic vehicles such as helicopters. During initial power-up each channel operates like a 1-channel sequential receiver. After four SVs have been acquired, one channel is dedicated to navigation (pseudorange measurements, carrier tracking, etc.) while the other channel reads the NAV message from each satellite. Both channels are also used to perform dual frequency measurements to compensate for ionospheric delay and to measure differential channel delay. Two-channel sequential receivers decrease the time it takes to start navigating by better than one minute when compared to 1-channel sequential receivers.

2.1.3 Multiplex (MUX) Receivers

A MUX receiver switches at a fast rate (typically 50 Hz) between the satellites being tracked, continuously collecting sampled data to maintain two to eight signal processing algorithms in software. In addition, the 50 Hz NAV message data is read continuously from all the satellites. In single channel MUX receivers the hardware channel is time shared and only one code generator and one carrier synthesizer is required to track the satellites. However, a multiplex receiver's measured carrier to noise ratio (C/N) for any satellite signal will be 10 log (n) (where n is the number of satellites being tracked) decibels (dB) below that of a continuous tracking receiver. Consequently, for military receivers, the MUX technique has the disadvantage of lower resistance to jamming and interference when compared to continuous tracking receivers. The MUX technique is more commonly found in commercial receivers where the reduced hardware cost can result in a less expensive product and where interference may be less of a concern.

2.2 "ALL-IN-VIEW" RECEIVERS

Traditionally, GPS receivers choose the four satellites of those available that give the best geometry to perform a position fix. However, in situations where one or more of the satellites are temporarily obscured from the antenna's view, the receiver will have to acquire additional satellite signals to generate a continuous PVT solution. The PVT solution degrades until the new satellites are acquired. One solution is to have a receiver which uses all available satellites in view to generate a solution. The inherent advantage of this receiver is that if it is tracking six or seven SVs and a satellite becomes obscured, the receiver will continue to provide a PVT solution with little, if any, degradation. In general, over-determined solutions improve accuracy of the receivers. If the receiver does not dedicate one hardware channel per satellite, then the receiver must use some sort of continual re-acquisition strategy (see MUX receivers paragraph 2.1.3).

2.3 AUTONOMOUS INTEGRITY MONITORING TECHNIQUES

GPS receivers may track additional satellites for integrity monitoring purposes. This function is independent of receiver architecture. Integrity monitoring receivers derive multiple position solutions by excluding one satellite at a time. Inconsistencies in the results are used to identify and exclude a faulty satellite. In general, at least five satellites must be tracked to detect an integrity failure, and at least six satellites must be tracked to exclude an erroneous satellite. Other measurements, such as altitude or time, may be substituted for satellites in the integrity algorithms, much in the same manner as these measurements are substituted in the PVT solution. In doing so, the integrity of the aiding sources is checked as well. The integrity monitoring algorithms are commonly referred to as Fault Detection and Exclusion (FDE) algorithms or as Receiver Autonomous Integrity Monitoring (RAIM or AIM) algorithms. These algorithms are typically executed on each new set of measurements, thus protecting the integrity of each PVT data set output by the receiver. For additional discussion of integrity, refer to Chapter 12.

2.4 TIME TRANSFER RECEIVERS

One of the more common uses of GPS is for precise time dissemination applications. Several manufacturers offer this type of equipment commercially. These precise time GPS receivers need only one GPS satellite for precise time dissemination if the receiver is stationary on a precisely known location and the only "unknown" is its own clock offset from GPS time and therefore from UTC. To obtain the necessary precise position, the receiver either receives it as an operator input or uses four satellites to determine its own position. These receivers typically include an internal oscillator or an optional external frequency source (rubidium or cesium). Whenever the receiver is tracking a satellite, it generates 1, 5, or 10 MHz reference frequencies that are synchronized to UTC time. If no satellites are visible, the reference frequencies are derived from the internal or external frequency source. The receivers can provide either stand-alone (uncoordinated) or coordinated time-transfer operations. In SPS receivers, use of SA will reduce the time and position accuracy available. The manufacturers of time transfer receivers claim time accuracies in the 20 to 50 nanoseconds range, but this accuracy requires algorithms that average pseudorange measurements over time (10 - 60 minutes). A stand-alone PPS time receiver normally provides time accuracy in the 100 nanoseconds range. The advantage of having an external frequency source interface designed into the receiver is that the long term error in the frequency source can be adjusted when the receiver has satellites in view. A stationary PPS GPS receiver with a precise time and time interval (PTTI) interface should be able to provide UTC to an accuracy of 50 to 60 nanoseconds.

2.5 DIFFERENTIAL GPS (DGPS) RECEIVERS

DGPS receivers are used in applications where enhanced accuracy of the PVT solution is required or desired. DGPS is based on the principle that receivers in the same vicinity will see similar errors on a particular satellite ranging signal. In general, the DGPS technique uses measurements from a reference receiver established at a known location, along with differencing algorithms, to remove common satellite and signal propagation errors from the PVT solutions of other (mobile) receivers operating in the vicinity of the reference station. The residual errors that remain uncorrected are due to multipath and noise in the receivers. DGPS techniques can be applied to the real-time PVT solution or to recorded measurement data. Real-time DGPS requires a data link pass the reference measurements to the mobile receiver(s). DGPS techniques can be applied to nondifferential receivers if the raw measurement data and navigation message are accessible. There are two primary variations of the differential techniques, one-based on ranging-code measurements and the other based on carrier-phase measurements.

Ranging-code DGPS (RCD) techniques can be applied to receivers with any of the tracking architectures described in the previous paragraphs. For RCD, measurements from the reference receiver are used at the receiver site to calculate corrections, which are then broadcast to the mobile receivers. The mobile receivers incorporate the corrections into their PVT solution, thereby removing the common errors and improving accuracy.

The reference receiver can develop corrections for the position solution or individual satellite ranging signals. If the corrections are provided for the position solution, the correction is simply the difference between the measured PVT solution and the "true" solution consisting of the surveyed location, zero velocity, and precise or smoothed time. However in this case, the reference and user receivers must either use the same satellites to calculate the same solution, or PVT corrections for each possible combination of satellites must be broadcast. It is usually more efficient and flexible to broadcast corrections based on individual satellite ranging errors, thereby allowing the user receiver to select the corrections that are applicable to the particular set of satellites that it is tracking. Real-time RCD is capable of producing accuracies on the order of 1 metre.

Carrier-phase DGPS (CPD) systems essentially calculate the difference between the reference location and the user location using the difference between the carrier phases measured at the reference receiver and the user receiver. In real-time systems, carrier-phase data from the reference receiver is broadcast to the mobile receivers. The mobile receivers use double-differencing techniques to remove the satellite and receiver clock biases, then use the phase differences to determine the position of the mobile receiver with respect to the reference receiver location.

Determining the initial phase offset (cycles plus fractional phase) between the reference station and the mobile receiver has traditionally been a process that required several minutes. Therefore, it is important to maintain phase-lock on the carrier signals to maintain a continuous flow of position data and avoid reinitialization. Consequently, CPD systems have traditionally used continuous tracking receivers. Receivers which gather measurements from more than four satellites are common since they add robustness in the event of loss-of-lock on one satellite and since additional satellites can reduce initialization time. The CPD techniques were originally developed for surveying applications where real-time data was not essential. However, near-real-time and real-time techniques are under development with the goal of supporting applications such as precision-approach for aircraft, as well as the original survey applications. Near-real-time and real-time range implementations can achieve centimeter accuracies (fractions of a carrier wavelength) and post-processing surveying techniques can achieve millimeter range accuracies. Surveying receivers are described in more detail in paragraph 2.6.

The accuracy of differential corrections developed at a single site will degrade with distance from the site due to increasing difference between the reference and mobile receiver ephemeris, ionospheric, and tropospheric errors. Such systems are usually called local area differential GPS systems (LADGPS). The accuracy of the corrections can be extended over a larger area by using a network of reference receivers to develop the corrections, and by modifying the correction algorithms in the user receiver. RCD systems which compensate for distance degradations are usually called wide area differential GPS (WADGPS) systems. CPD systems which compensate for distance degradations are usually called very long baseline interferometry (VLBI) systems.

CPD techniques (interferometry) can also be used to determine platform attitude. In this case, the processing can be contained within one receiver using multiple antennas. The distinction is lost between which antenna is the "reference" and which is "mobile," since all are located at fixed positions on the platform and none are located at surveyed positions with respect to the earth. Since the antennas are separated by fixed distances, and since their relationship to the center-of-mass of the platform is known, it is possible to convert the carrier phase differences into angular differences between the antenna locations and the line of sight to a satellite. By using measurements from multiple satellites, or the position of the platform from a GPS position fix, these angular differences can then be transformed to represent the attitude of the platform with respect to the local vertical axis.

There are several standard (and numerous proprietary) broadcast protocols, receiver interfaces, data formats, data sets, and sets of algorithms that have been developed for DGPS applications. Consequently DGPS receivers are typically designed with a particular application in mind and may not be suitable for a different application. Similarly, proprietary systems may not be compatible for the same application. Therefore, DGPS requirements should be investigated thoroughly and candidate DGPS receivers or systems should be evaluated for suitability and compatibility.

2.6 SURVEYING RECEIVERS

Formal surveys are typically conducted with one surveying receiver located in a previously surveyed location and a second receiver at the new location to be surveyed. The receiver at the previously surveyed location acts as a DGPS reference receiver and the receiver at the new location acts as a DGPS "mobile" receiver. The "mobile" receiver is usually fixed at the new location for a period of time to collect redundant measurements and further improve the accuracy of the survey by post-processing to remove or reduce residual errors such as receiver measurement noise. The period of time can range from seconds to days depending on the survey accuracy required. Consequently, surveying

receivers must include considerable data recording capability. They may also include the capability to store additional information about the characteristics of the surveyed site.
Many surveying receivers have the capability to do a "self-survey", that is, develop a smoothed or averaged position from non-differential GPS measurements. Non-differential (absolute) surveys require considerably more time than DGPS surveys to develop the same accuracy. However, the technique can be useful to establish a reference point for subsequent DGPS (relative) surveys at locations where a formal reference point is inconvenient or unavailable. This capability can be especially valuable for tactical military survey applications where the relative location of the surveyed sites is more important than the absolute location or where centimeter accuracy is unnecessary.

Most surveying receivers can also function in some capacity as navigation receivers, thereby providing guidance for the surveyor to previously surveyed sites. Additional software functions may also be provided to support datum transformations, post-processing, and other related survey functions.

The signal processing techniques of GPS surveying receivers can be divided into four categories:

a. Non-differential GPS
b. Ranging-Code Differential
c. Carrier-Phase Differential (Interferometry)
d. Codeless Carrier-Phase Differential

As described above, many surveying receivers have a non-differential GPS mode for navigation and self-surveys. The signal processing techniques and accuracies obtained are similar to other non-differential receivers as described in Chapter 1. Surveying receivers may use RCD to determine an initial survey position that aids the initialization process. The more accurate the initial position, the more quickly initialization can be completed for real-time applications. Even if the final results are post-processed to obtain maximum accuracy, real-time outputs can provide preliminary results that confirm the success of the survey in the field or enable the surveyor to detect and correct problems that may occur. The primary surveying mode of most surveying receivers is CPD. The carrier-phase measurements and algorithms enable centimeter and sub-centimeter accuracies in part due to significantly lower measurement noise when compared to pseudorange measurements. As in non-differential GPS, ionospheric errors can contribute significant errors. However, in surveying applications, dual frequency (P-code) measurements are almost essential to achieve surveying accuracies. Since the P-code is normally only available as the Y-code, most surveying receivers use a "codeless" technique to perform ionospheric delay measurements. One technique uses spectral compressors to compress the GPS signals into audio or subaudio bands. A processor is used to extract the frequency and phase of each satellite in view. Another technique is to split the received satellite signal and multiply it by itself to obtain a second harmonic of the carrier phase shift which does not contain the code modulation. Codeless techniques can also be used to make CPD measurements but the C/A-code navigation message must also be read to obtain the satellite ephemeris if real-time outputs are desired.

2.7 ANALOG/DIGITAL RECEIVERS

The majority of early GPS receiver designs made extensive use of analog signal processing techniques, however, most modern receivers incorporate digital signal processing to replace analog receiver functions wherever possible. The following examples are provided to give a description of the differences between these two design techniques. Figure 2-1 shows a multichannel GPS receiver in which code correlation is performed using analog mixing techniques at the intermediate frequency (IF). Each satellite signal to be tracked requires a separate hardware processing channel which consists of an analog correlator, code translator, IF stage, and base band converter. The bandwidth of the IF stage is designed to accommodate the GPS data rate and maximum carrier doppler-shifted frequency.

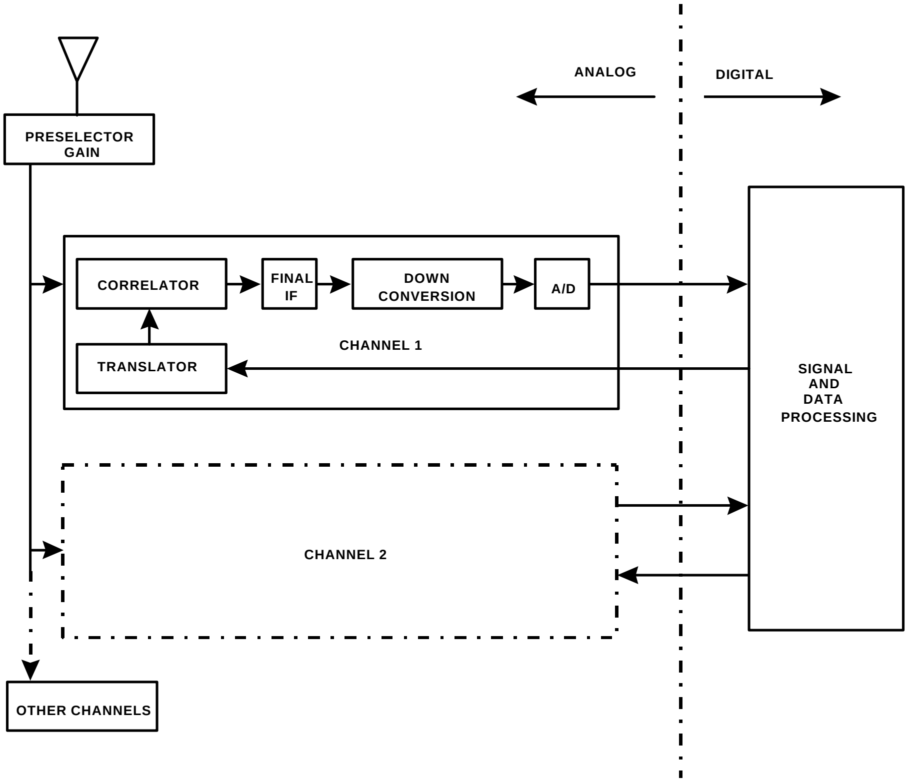


Figure 2-1. Analog GPS Receiver Architecture

Figure 2-2 illustrates a GPS receiver using a largely digital architecture. Analog signal processing is limited to preselection and gain applied to the GPS signals during down conversion with fixed translation frequencies. The down-converted signals are digitized through sampling and are then ready for further digital processing. The digital signal processor (DSP) functions shown in Figure 2-2 include correlation, code and carrier acquisition, and data recovery.

In a digital receiver, analog to digital (A/D) conversion takes place at the receiver IF. Code correlation and further signal processing occurs digitally. Since the input signals remain code division multiplexed throughout the front end, this portion of the receiver can accommodate either a sequential or multiplexed tracking configuration for any number of satellites. Thus a digital receiver can easily be structured as an "all in view" receiver, whereas an analog equivalent would require a dedicated hardware correlation channel for each satellite in view. The digital architecture illustrated in Figure 2-2 also provides for a great reduction in complexity of the analog portion of a receiver. This in turn results in lower production costs for test, calibration, and maintenance.

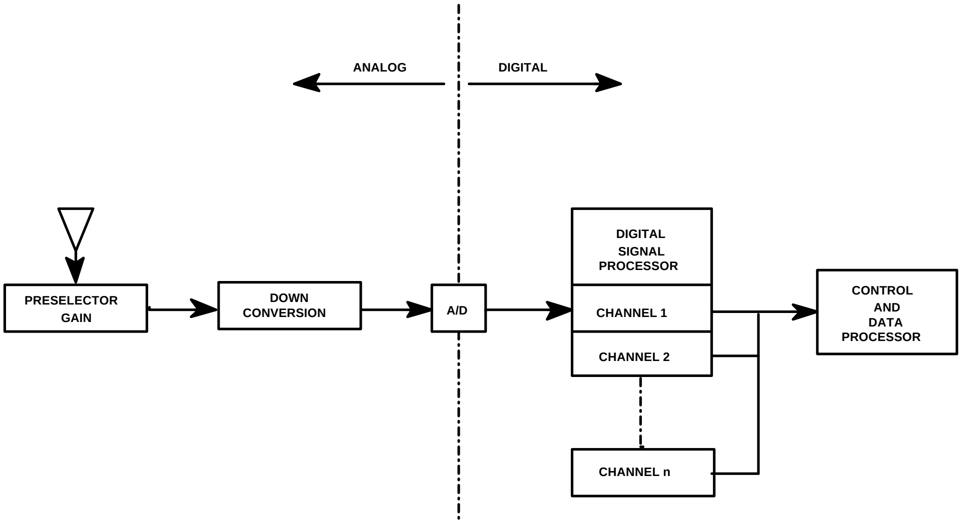


Figure 2-2. Digital GPS Receiver Architecture

2.8 GPS AS A PSEUDORANGE/DELTA RANGE SENSOR

A GPS receiver need not necessarily be used as a PVT sensor in an integrated navigation system. An integrator may instead wish to use GPS to supply satellite pseudorange and deltarange measurements to an integrated positioning solution. Additional measurements may be provided to the integrated solution by systems or equipment such as an Inertial Navigation System (INS) (position, velocity, acceleration, attitude), Doppler Navigation System (position, velocity), Inertial Aircraft Heading Reference System (velocity, acceleration, attitude), or a Central Air Data Computer (CADC) (baro-altitude and airspeed). The positioning processor can combine all the measurement data into one Kalman filter, to generate a system positioning solution.

Such a solution requires a sophisticated integration scheme. In order to use the pseudorange and deltarange data, additional information is needed such as satellite ephemeris and GPS receiver clock biases. Accurate system and subsystem clocks are needed to correct for differences between the time the calculations are performed and the time that the measurements were taken. Alternatively, measurements can be deweighted in the integrated solution and latency errors added to the system error budget. If implemented correctly, a GPS sensor can still contribute to a navigation solution when less than four satellites are being tracked. Such a system is capable of incorporating a single satellite measurement into the system Kalman filter, thus bounding the navigation system solution in one dimension. The disadvantage of using GPS as a sensor in an integrated positioning solution is the high level of complexity involved in integrating such a system.

In general, stand-alone GPS receivers do not allow corrected pseudorange and delta range data out of the receiver since it is classified data. Therefore, some receivers provide the capability to process the integrated solution within the GPS receiver. Many GPS sensors are now small enough to be embedded as a card or module into another system, such as an INS or Flight Management System (FMS). In such cases, the corrected pseudorange and delta range data may be permitted off the card or module since the classified data would be contained within a single unit. However, GPS technology now allows most of the GPS receiver functions to be performed by a single semiconductor chip or small chip set. Consequently, future security/processor devices such as the Selective Availability Anti-Spoofing Module (SAASM) may return to the "stand-alone" architecture, providing the capability to process the integrated solution aboard the device, while not allowing the corrected pseudorange and delta range data out of the device. For additional discussion of GPS integration architectures and related issues, refer to Chapter 8. For security design guidelines refer to Navstar GPS PPS Host Application Equipment (HAE) Implementation Guidelines.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 3: MINIMUM PERFORMANCE CAPABILITIES OF A GPS RECEIVER

3.1 BASIC CONSIDERATIONS

There are a set of basic performance parameters that are useful for making comparisons between different GPS receivers. This set of parameters, together with others, can be used to determine what type of receiver one should choose for a particular application. The parameters of interest are:

a. Position accuracy
b. Velocity accuracy
c. Time accuracy
d. TTFF

3.1.1 GPS System Accuracy Characteristics

There are a number of different ways in which to express GPS accuracy. All are expressed in statistical terms, with a probability assigned to the value given, and the number of dimensions expressed or implied. The two primary positioning accuracy requirements imposed on the GPS system by the U.S. DoD are 16 metres SEP for PPS, and 100 metres 95% horizontal for SPS. SEP represents a 50% probability. Note that the PPS requirement is a three-dimensional requirement specified at the 50% probability level and the SPS requirement is a two-dimensional requirement specified at the 95% probability level. Despite this inconsistency, these are the parameters and points on the accuracy distributions that the Control Segment has used to determine system management policies and methods.

GPS system positioning accuracy distributions are not spherical and are not Gaussian in the tails of the distributions. Consequently, conversions from the system accuracy requirements to other expressions of GPS accuracy, based on an assumption of a spherical distribution that is Gaussian in each dimension can be inaccurate, especially at the 95% probability level which is commonly used by NATO.

"Technical Characteristics of the Navstar GPS" gives conversions of the PPS positioning requirement for typical GPS system operating conditions as 37 metres 95% spherical accuracy and 21 metres 95% horizontal accuracy. Technical Characteristics of the Navstar GPS also provides 95% accuracy tables to facilitate comparisons of PPS and SPS spherical, horizontal, and vertical accuracies.

GPS exhibits statistical accuracy distributions because two important parameters determine the accuracy of the position solution. They are User Equivalent Range Error (UERE) and Geometric Dilution of Precision (GDOP). Both of these parameters are variable with time. UERE is a measure of the error in the range measurement to each satellite as seen by the receiver. UERE varies because of random variations in the satellite signal, signal propagation characteristics, and user measurement processes. Over the long term (days to months) UERE closely resembles a Gaussian distribution and is equivalent for each satellite. UERE tends to be different for each satellite at any instant in time and tends to be at a minimum following a new navigation message upload.

GDOP is an instantaneous measure of the error contributed by the geometric relationship of the satellites as seen by the receiver. GDOP is a dimensionless multiplicative factor. For a given value of UERE, small GDOP values mean more precise position and/or time. GDOP varies because the satellites are in constant motion and their geometric relationships are constantly changing. Consequently GDOP can vary with time and user location. The "average" GDOP tends to induce a circular error distribution in the horizontal plane with the vertical contribution of error approximately 1.5 times the horizontal contribution. In real-time, GDOP can be asymmetrical in the three dimensions and vary significantly from the average or typical case, however, GDOP can be easily measured by the receiver, and is often used to select optimum combinations of satellites for the position solution or to develop real-time accuracy estimates.

GDOP distributions are not Gaussian, particularly in the tails of the distribution. The global distribution of GDOP can vary significantly at the 95% probability level due to temporary "vacancies" in the GPS constellation, while remaining relatively constant at the 50% probability level where the GPS PPS system accuracy requirement (16 metres SEP) is defined. Therefore, PPS 95% accuracy specifications derived from this requirement may not be rigorously maintained through all the possible states of the GPS constellation. However, although small variations in accuracy performance are likely with each change in the constellation state, worst-case situations are worst-case for all users and by all measures of system performance, and will therefore be avoided or quickly corrected by the Control Segment. (Temporary "vacancies" in the satellite constellation can be expected over the life of the system due to preventive maintenance, satellite end-of-life failures and delayed replacements, or random satellite failures that are correctable by the Control Segment.)

UERE and GDOP are explained in more detail in paragraphs 3.1.2 and 3.1.3. It should be noted that these errors are constantly present as normal variations in accuracy, even with a complete GPS constellation and correctly operating satellites, Control Segment, and receiver.

3.1.2 GPS PPS System Range-Error Budget

The GPS PPS system range-error budget is presented in Table 3-1. The budget is expressed for the 95% probability level of the system UERE. This is a UERE averaged for all satellites over a 24-hour period. Therefore, the long-term (greater than 24 hours) one-sigma UERE for an individual satellite can exceed this value and the system can still meet the accuracy requirements specified in the previous paragraph. The instantaneous UERE of all satellites will typically exceed this value at sometime during a 24 hour period. From the user point of view, the important values in this error budget are those allocated to the User Segment. These are excellent guidelines for the purchase or development of receivers because they are independent of the performance of the Space and Control segments.

Table 3-1. GPS PPS System Range Error-Budget

Segment	Error Source	UERE Contribution (metres, 95%)	
		P-Code	C/A-Code
Space	Frequency Standard Stability	6.5	6.5
	D-Band Delay Variation	1.0	1.0
	Space Vehicle Acceleration Uncertainty	2.0	2.0
	Other	1.0	1.0
Control	Ephemeris Prediction and Model Implementation	8.2	8.2
	Other	1.8	1.8
User	Ionospheric Delay Compensation	4.5	9.8-19.6
	Tropospheric Delay Compensation	3.9	3.9
	Receiver Noise and Resolution	2.9	2.9
	Multipath	2.4	2.4
	Other	1.0	1.0
Total (RSS) System UERE (metres, 95%)		13.0	15.7-23.1

3.1.2.1 GPS UE Range-Error Budget

The portion of the UERE allocated to the Space and Control segments is called the user range error (URE) and is defined at the phase center of the satellite antenna. The portion of the UERE allocated to the user equipment is called the UE error (UEE). Specifically, the UERE is the root-sum-square of the URE and UEE. The UEE includes residual errors after compensation for atmospheric delay, inherent receiver errors of noise and resolution, and multipath. Modern C/A-code receivers have demonstrated significant improvements in ionospheric delay compensation over the budgeted values. The values given for ionospheric delay compensation error are based on dual-frequency delay measurements for P-code and the single-frequency ionospheric delay model for C/A-code (as specified in "Technical Characteristics of the Navstar GPS"). The budgeted values for C/A-code can be improved by use of a modified single-frequency model or code less dual-frequency measurements on the L1 and L2 carriers. Modern P-code and C/A-code receivers have both demonstrated significant improvements over the budgeted values for receiver noise, resolution, and multipath, using digital phase locking techniques and variable or narrow code correlation techniques.

3.1.3 Geometric Dilution of Precision

As described in paragraph 3.1.1, GDOP is a dimensionless multiplicative factor that is an instantaneous measure of the error in the positioning solution, contributed by the geometric relationships of the GPS satellites, as seen by the receiver. As an example, if two lines of position are necessary to establish a user position, the least amount of error is present when the lines cross at right angles. The greatest error is present as the lines approach parallel. (See Figure 3-1.) Similarly, for GPS, the greatest amount of error is present when the lines-of-sight between the user and 2 or more satellites approach parallel, or when all four satellites approach the same plane.

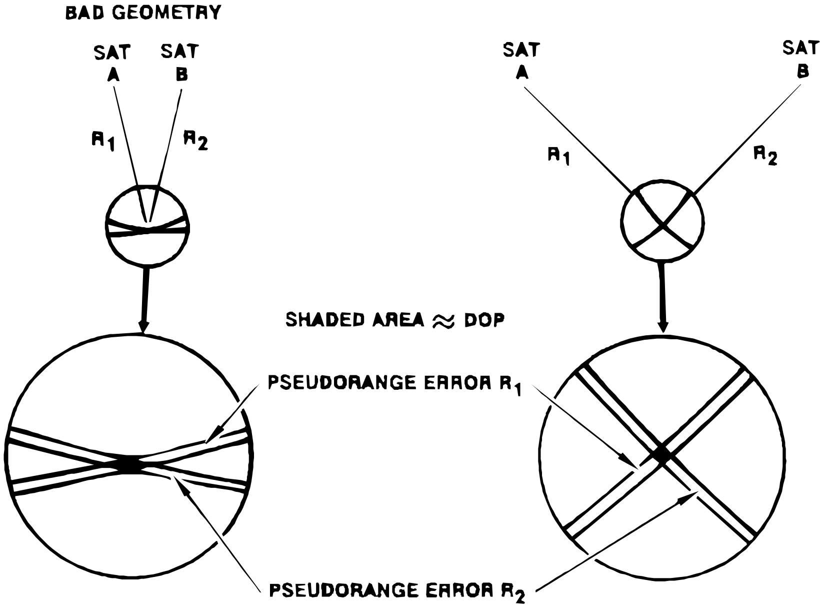


Figure 3-1. Dilution of Precision

"Technical Characteristics of the Navstar GPS" contains the mathematical definition and derivation of GDOP. In short, if the one-sigma pseudorange measurement errors for all satellites are assumed to be unity, GDOP is defined to be the square root of the sum of the variances of the position and time error estimates.

GDOP = $(s_x^2 + s_y^2 + s_z^2 + c^2 s_t^2)^{1/2}$

(Where "c" is the speed of light and "t" is the user clock bias.)

GDOP is therefore considered to relate the standard deviation of the satellite range errors (UERE) to the standard deviation of the position solution errors. GDOP is normally considered to be unitless; the units (metres) being carried by the range error and position solution errors. Expressed as a mathematical formula:

s_{UERE} x GDOP = $s_{\text{POSITION SOLUTION ERROR}}$

Other dilution of precision factors can be defined which are a subset of GDOP and have a more specific physical meaning with respect to the x, y, and z axes in a local coordinate system. They include position dilution of precision (PDOP), horizontal dilution of precision (HDOP), vertical dilution of precision (VDOP) and time dilution of precision (TDOP). Mathematically they are defined as follows:

$$\text{PDOP} = (s_x^2 + s_y^2 + s_z^2)^{1/2}$$

$$\text{HDOP} = (s_x^2 + s_y^2)^{1/2}$$

$$\text{VDOP} = (s_z^2)^{1/2}$$

$$\text{TDOP} = (s_t^2)^{1/2}$$

HDOP can be further resolved into its X and Y components. If the X axis is oriented in an East-West direction, an "East" DOP (EDOP) and "North" DOP (NDOP) can be defined as follows:

$$\text{EDOP} = (s_x^2)^{1/2}$$

$$\text{NDOP} = (s_y^2)^{1/2}$$

Similarly, if the Y axis is oriented along the track of a moving vehicle, a "cross-track" DOP (XDOP) and an "along-track" DOP (ADOP) can be defined:

$$\text{XDOP} = (s_x^2)^{1/2}$$

$$\text{ADOP} = (s_y^2)^{1/2}$$

The various elements of GDOP can also be calculated for an over-determined position solution, that is, where the available satellite or aiding measurements exceed the required minimum of four, and an "all-in-view" solution is calculated. The mathematical formulations are similar, and generally result in a lower value of GDOP (hence better solution accuracy) for each additional measurement that is added to the calculation.

GDOP can also be "weighted" with a vector of UERE values in the matrix calculations for real-time or short-term error estimates where the satellite (or aiding) UERE values are not equal. As mentioned previously, this is generally the case for instantaneous values of UERE, and especially true for SPS where large differences in instantaneous UERE can be caused by Selective Availability. This is also true for aiding situations where the equivalent "UERE" of the aid is usually different than the typical satellite UERE. This "weighted" variation of DOP is an estimate of User Navigation Error (UNE) and is sometimes termed "KDOP". KGDOP has the same definition as GDOP except that the statistical satellite range errors are not required to be equal. Similarly there are analogous subset definitions of KPDOP, KHDOP, etc.

Which DOP value may be most relevant to a particular application is dependent on the mission and associated accuracy requirements of that mission. (K)HDOP may be most important for land and open ocean navigation where horizontal position location and rendezvous are primary mission requirements. (K)XDOP and (K)ADOP may be most important for air navigation where aircraft spacing is a primary safety consideration. (K)PDOP may be most important for aircraft weapons delivery, and (K)TDOP is obviously most important for time transfer applications. Note that the DOP values discussed here are instantaneous estimates of the geometric contribution to error for a particular location and time. System accuracy requirements often require estimates of long-term error distributions.

For long-term error estimates, the relationship between range error and position solution error should be determined by computer simulation. The standard deviation of the long-term position error distribution can be determined by using the standard deviation of GDOP and the standard deviation of UERE, but the relationship does not hold true for other probability levels, because the tails of the GDOP and position solution distributions are not Gaussian. The most effective method for determining long-term error distributions, for a particular constellation state or set of states, is by conducting a computer simulation.

Computer simulations can be performed to determine global, regional, or single location distributions, but they are often complex and time consuming. If a Monte Carlo simulation is performed assuming a one-metre standard deviation for UERE, the resultant normalized position error (NPE) distribution can be scaled by any UERE of interest, and examined at any probability level of interest. The simulation can iterate user locations around the globe and satellite orbital locations over time (24 hours) while simulating GPS receiver calculations to determine the NPE distribution. While NPE is analogous to GDOP in that it is a measure of the geometric characteristics of error, GDOP is an instantaneous measure and NPE is a statistical measure. The 95% PPS and SPS accuracy values given in paragraph 5.1 of "Technical Characteristics of the Navstar GPS", were determined by an NPE simulation using an optimized 21 satellite constellation as a surrogate for the average or typical state of the GPS constellation.

It should be emphasized that it may be perfectly valid to translate user accuracy requirements between different dimensions and probability levels assuming a spherical error distribution and Gaussian error characteristics, if that is appropriate for the particular mission or application. The fact that GPS accuracy performance is nonspherical and non-Gaussian does not impose a similar condition on user requirements.

3.2 RECEIVER POSITION ACCURACY

As described in paragraph 3.1.2.1, the UEE is independent of the satellite and Control Segment errors, URE and receiver position accuracy are not. Therefore, receiver position accuracy must be specified for conditions of DOP and URE, in order to isolate the receiver contribution to position accuracy (e.g., UEE, filtering algorithms, and coordinate transformations). Dynamic positioning accuracy requirements must take into account the effect of vehicle motion on the filter accuracy as well. Laboratory testing must control DOP and URE. Field testing must record DOP and URE. In general, testing is best performed when the system positioning accuracies can be achieved. Assuming the UERE error budget is maintained, this generally means DOP conditions of PDOP < 6, HDOP < 4, VDOP < 4.5, and TDOP < 2. URE and DOP are best measured during tests by a calibrated reference receiver. Computer programs which use the broadcast almanac to predict periods of favorable DOP can assist field test scheduling. The GPS System Effectiveness Model (SEM) is one such program developed for the GPS JPO and has been distributed to all NATO nations. Other similar programs are commercially available.

3.3 RECEIVER VELOCITY ACCURACY

GPS receivers typically calculate velocity by measuring the frequency shift (Doppler shift) of the GPS D-band carrier(s). Velocity accuracy can be scenario dependent, but 0.2 m/sec per axis (95%) is achievable for PPS receivers. SPS velocity accuracy is the same as PPS when SA is off. When SA is on, SPS velocity accuracy is degraded. The amount of degradation of the velocity is classified. However, although not guaranteed, SPS velocity accuracies around 0.4 m/sec 95% have been observed by civilian users for the typical level of SA associated with normal peacetime operations and 100 metres 95% horizontal positioning accuracy.

Velocity accuracy can be effectively tested in a laboratory environment, but field testing can be difficult since a tracking system with 0.05 m/sec or better accuracy is required. The reader is urged to carefully consider the methods of testing if velocity accuracy is an important mission requirement.

3.4 RECEIVER TIME ACCURACY

A dedicated PTTI port should normally be used for precise time output from a GPS receiver. Significant time delays and uncertainties from microseconds to milliseconds can be introduced if time output is accomplished via a digital data interface. For a PPS P-code GPS receiver, tracking 4 satellites, an absolute time accuracy of better than 200 nanoseconds (95%) relative to UTC is possible in a stationary or low-dynamic situation at an unsurveyed location. Equivalent SPS C/A-code accuracy is 340 nanoseconds (95%). Higher dynamics will increase time error. Errors in the PTTI output result from errors in the GPS receiver as well as the Control and Space segments. The system time transfer error budget is shown in Table 3-2.

Processing errors in the GPS receiver and unaccounted time delays to propagate the timing pulses to the PTTI port can add another 60-100 nanoseconds (95%), depending on receiver design. Therefore, a total (RSS) time error of 209-224 nanoseconds (95%) can be expected.

Typical 95% time accuracies expected for precise time dissemination for different categories of GPS receivers are shown in Tables 3-3 and 3-4, assuming an RSS of 88 ns for the Control and Space Segment errors, and 78 ns for the PTTI error.

3.5 TIME-TO-FIRST-FIX

Time-To-First-Fix (TTFF) is a measure of the elapsed time required for a receiver to acquire the satellite signals and navigation data, and calculate the first position solution. TTFF begins when initialization of the receiver is complete (including self-test, loading of PPS keys, and any required operator input) and the receiver is commanded to begin the positioning function. Some source material (U.S. DoD in particular) may refer to TTFF1 and TTFF2. TTFF1 is based on C/A-code acquisition with hand over to P-code tracking. TTFF2 is based on direct P-code acquisition. REAC (reaction time) is the term typically used to include both the initialization process and TTFF. Since initialization may necessitate operator action, REAC specifications or requirements may require assumptions of operator response times. TTFF is a function of the initial receiver state as well as receiver design. The following paragraphs describe the satellite acquisition and initial positioning processes in more detail.

Table 3-2. Time Error Budget

Error Component	Error (ns, 95%)
US Naval Observatory Measurement Component	137
Control Segment Measurement Component	59
GPS Time Predictability	92
Navigation Message Quantization	6
Satellite Orbit	22
Satellite Clock	63
Satellite Group Delay	12
Downlink and User Equipment	65
Total (RSS) Time Transfer Error Budget	199

Table 3-3. Precise Time Output Accuracy (95%)
for a Typical PPS P-code Receiver

Receiver Mode	Receiver Output	S/A On	S/A Off
Stand-Alone, Stationary, or Low Dynamic	Instrumentation Port	2 ms	2 ms
	PTTI Port	127 ns	127 ns

Table 3-4. Precise Time Output Accuracy (95%)
for a Typical SPS C/A-code Receiver

Receiver Mode and Output	S/A On	S/A Off
Stand-Alone (4 SVs), Stationary or Low Dynamic, PTTI Port	274 ns	157 ns
Stand-Alone (1 SV), Stationary, Known Position, PTTI Port	255 ns	147 ns
Coordinated Time Transfer, PTTI Port	59 ns	20 ns
Instrumentation Port	2 ms	2 ms

3.5.1 Warm Start, Cold Start, and Hot Start

Three different variations of TTFF are commonly defined and any one or all three can be specified or required for a particular receiver. A warm or normal start is based on the assumption that the receiver has an estimate of current time and position as well as a recent copy of the satellite almanac data. Typically, time should be known within 20 seconds of GPS time, position should be known within 100 kilometers, velocity within 25 metres per second, and the satellite almanac should have been collected within the past few weeks. TTFF1 for warm starts is typically in the 2 to 5.5 minute range.

A cold start occurs whenever there is a problem with these key data elements. This is typical of a receiver as delivered from a manufacturer, supply depot, or repair depot. Date and time will not be maintained if the receiver "keep alive" battery has been removed or drained. If the receiver clock and memory remains active, the last known position might be at a factory or depot thousands of kilometers from the present position, and the almanac may be several months old. Under such conditions, the receiver may have to systematically "search the sky" until it can find a satellite and retrieve time and a current almanac. A cold start can add at least 12.5 minutes to TTFF1 over that based on a warm start.

A hot start occurs when a receiver is provided with a standby feature to maintain oscillator temperature, time, position, and individual satellite ephemerides (as well as the almanac). When the receiver is commanded out of the standby mode, the time required to achieve the next full position fix is usually Termed Time to Subsequent Fix (TTSF) rather than TTFF. Typically, TTSF is on the order of 10 seconds for standby periods of a few hours.

3.5.2 Receiver Warm-Up

When a GPS receiver is initially turned on, time must be allowed for the receiver crystal oscillator to warm up and stabilize at its normal operating temperature. In a GPS receiver it typically takes up to 6 minutes to complete this process. If the receiver is provided with a mode that keeps the oscillator warm, this contribution to TTFF can be avoided.

3.5.3 Almanac Collection

The first time a receiver is operated, it must perform an iterative search for the first satellite signal unless it can be loaded with a recent satellite constellation almanac, the approximate time and the approximate receiver location. The almanac gives the approximate orbit for each satellite and is valid for long time periods (up to 180 days). The almanac is used to predict satellite visibility and estimate the pseudo-range to a satellite, thereby narrowing the search window for a ranging code. Once the first satellite signal is acquired, a current almanac can be obtained from the NAV msg. It takes up to 12 1/2 minutes to collect a complete almanac after initial acquisition. An almanac can be obtained from any GPS satellite. Most modern receivers can update the almanac periodically and store the most recent almanac and receiver position in protected memory. A clock can also be kept operating when the receiver is off or in standby mode, so as to minimize initial acquisition time for the next start-up.

3.5.4 Initial Uncertainties

The initial uncertainties associated with a GPS receivers initial position, velocity, acceleration, jerk and time inputs must be specified when satellite acquisition times are being tested. Acquisition and reacquisition times will vary depending on the accuracy of the receiver initialization. Some military TTFF requirements that include jamming and other sensitive parameters in the start-up scenario may be classified.

3.5.5 Ephemerides Collection

Ephemeris data forms part of the 50 Hz NAV msg transmitted from the GPS satellites. Unlike almanac data which can be obtained for the whole constellation from a single satellite, ephemeris must be collected from each satellite being tracked on acquisition and at least once every hour. Ephemeris information is normally valid for 4 hours from the time of transmission, and a receiver can normally store up to 8 sets of ephemeris data in its memory. Acquisition and reacquisition times for a receiver will vary, depending on whether valid ephemeris data is already available to the receiver. When testing acquisition time it is necessary to specify whether a valid set of ephemerides is resident or not within the receiver. Depending on the NAV msg collection scheme employed in a particular receiver, it can take between 30 seconds and 3 minutes to collect the ephemeris information.

3.5.6 Enhanced Acquisition Techniques

A number of enhanced acquisition techniques have been developed for modern receivers. TTFF performance can be significantly improved by the use of multi-tap correlators and multi-channel search algorithms. Multi-tap correlators are essentially multiple correlators in the same package which greatly enlarge each search window for code correlation. Similarly, using all available receiver channels in the search for the first satellite can reduce TTFF by maximizing the effective search window of the receiver.

3.5.7 Direct P(Y)-Code Acquisition

Direct P(Y)-code acquisition can be effectively achieved using enhanced acquisition techniques to enlarge the search window and/or by using atomic clock aiding to reduce the initial time uncertainty. Similarly, aiding from an inertial reference system can be used to reduce the initial velocity and position uncertainty. Downloading initialization data from another receiver can be used for direct P(Y)-code acquisition as well.

3.5.8 TTFF Requirements

Figure 3-2 is a decision chart for determining TTFF requirements for the various initial conditions described above, as well as the TTFF1 and TTFF2 acquisition strategies and different receiver designs

3.5.9 Satellite Reacquisition

Satellite reacquisition assumes a temporary loss of a satellite signal due to masking or similar loss of satellite visibility. A satellite reacquisition time of 10 seconds or less is typically achievable. As described in paragraph 3.5.3, the accuracy of the receiver position estimate is a primary factor in determining satellite reacquisition time. Vehicle dynamics and elapsed time from loss of the signal are therefore important in determining the accuracy of the receiver position estimate, as is the presence of GPS aids such as an INS. Laboratory testing is recommended since these factors are difficult to control and predict in the field.

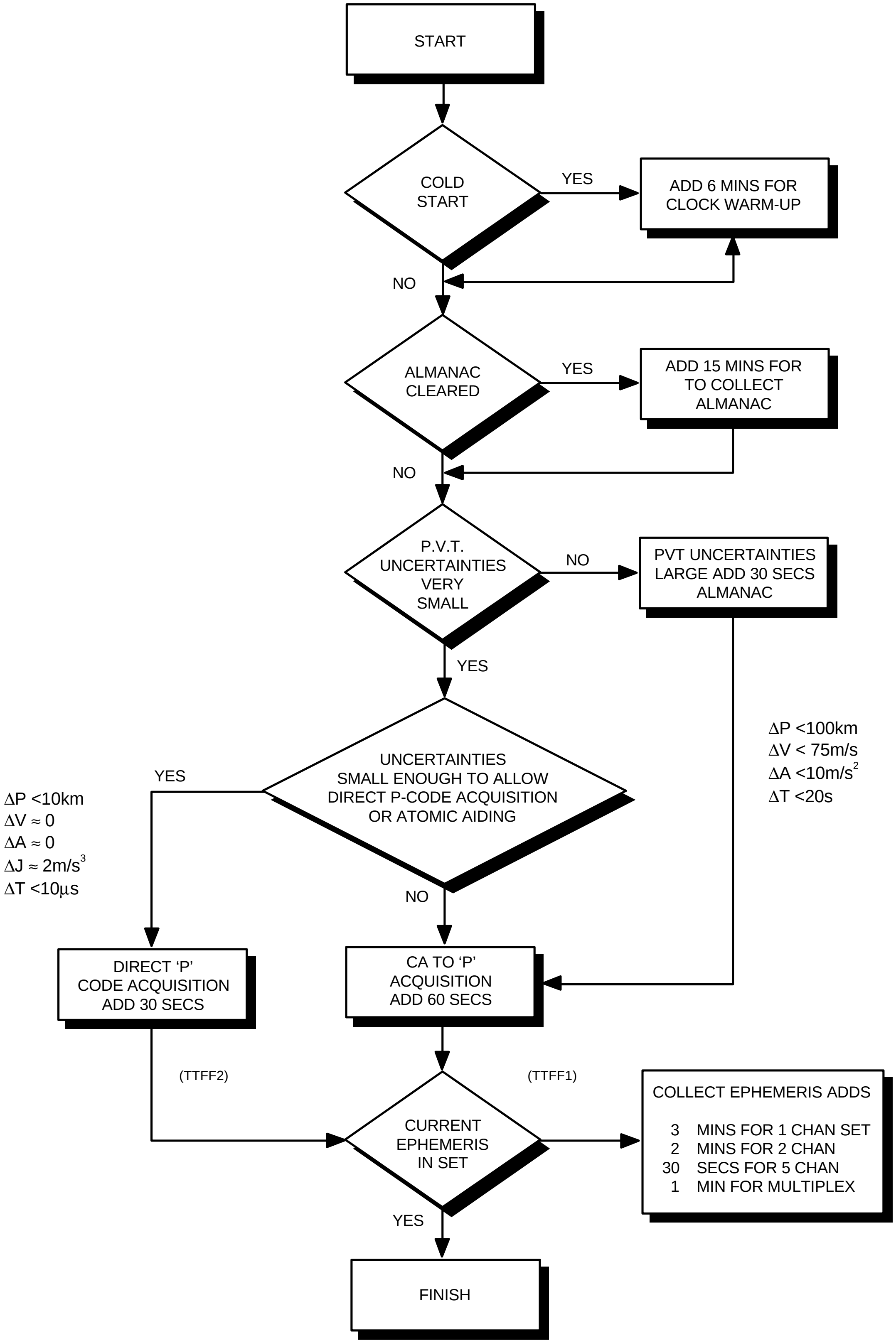


Figure 3-2. Time-To-First-Fix (TTFF)

CHAPTER 4: GPS RECEIVER INTERFACES AND ANCILLARY EQUIPMENT

4.1 INTRODUCTION

GPS receivers often require electrical interfaces with other components of the GPS receiver system or with other systems in a host vehicle (HV). Virtually all vehicle integrations will require interfaces with HV power and an external antenna. Many will require a crypto key interface and control-and-display interfaces between an equipment compartment and a crew compartment. Some will require interfaces between a data loader and the GPS receiver. Others may require interfaces between the GPS receiver and other navigation systems in order to develop an integrated position solution. In order to accommodate the varied requirements of different installations, a GPS receiver may be built with a variety of interfaces to aid integration. This chapter presents some thoughts on the ways of integrating GPS with other systems using the interfaces specified for many of the U.S. DoD receivers. These interfaces are also used by other NATO Nations and are provided by other manufacturers, and therefore give an indication of what type of interfaces could be available in a military GPS receiver. Examples of U.S. DoD ancillary equipment are also provided to clarify interface uses.

4.2 GENERAL PURPOSE INTERFACES

Two of the most used interfaces in a vehicle integration are the MIL-STD-1553 multiplex data bus and the ARINC 429 digital information transfer system. Both interfaces can be used to interconnect a GPS receiver with a wide variety of other equipment, for example, a control-and-display unit (CDU), data loader, flight instrument interface unit, or other navigation system such as an INS.

4.2.1 MIL-STD-1553 Multiplex Data Bus

Some GPS receivers are designed to communicate with other equipment via a MIL-STD-1553 interface. The MIL-STD-1553 data bus is commonly used aboard military aircraft and can also be found aboard military ground vehicles, ships, and missiles. It is seldom used for civilian applications. The MIL-STD-1553 bus operates with one of the interconnected equipment units assigned as a bus controller. The bus controller controls the data flow on the bus in an asynchronous command/response mode, and also transmits and receives information. The other units are connected to the bus function as "slaved" remote terminals that receive and transmit information, but may also function as back-up bus controllers. The bus controller software program is specifically designed for each unique installation.

4.2.2 ARINC 429 Digital Information Transfer System

The ARINC 429 data link is commonly used in commercial as well as military aircraft. It is a single-point to multi-point asynchronous half-duplex data link. That is, an equipment can transmit data to several other pieces of equipment. Each link is programmed to output specific data formats at specific data rates. The ARINC 429 specification defines standard data formats and rates for data transfer between a wide variety of commercial avionics equipment. However, the GPS data formats were designed for a commercial ARINC 743A GPS/ GLONASS receiver.

4.2.3 Uses of the MIL-STD-1553 and ARINC 429 Interfaces

The following paragraphs give several examples of ancillary equipment that might communicate with a GPS receiver over the MIL-STD-1553 or ARINC 429 data links.

4.2.3.1 Control and Display Unit

A CDU is often required when a GPS receiver in an equipment compartment must be controlled remotely from a crew compartment. The CDU allows the operator to enter initialization data and control parameters, display status and position data, and can provide access to related functions, such as, waypoint navigation functions. Examples of two types of CDUs procured by the U.S. DoD are discussed below to clarify typical CDU capabilities.

The U.S. DoD has procured dedicated CDUs as well as multifunction CDUs. A dedicated CDU (or "dumb" CDU) is essentially a remote control and display panel that possesses no processing capability, relying on the GPS receiver for all computation functions. A multifunction CDU (or "smart" CDU) is designed to control a GPS receiver, perform other navigation or control functions, and may interface with additional navigation equipment as well. The multifunction CDU includes onboard processing capability for functions, such as, calculating a composite positioning solution using GPS and other navigation sensors, or performing the waypoint navigation function.

4.2.3.1.1 Dedicated CDU

A view of the front panel of a dedicated CDU with a sample display is shown in Figure 4-1. The CDU has a four line, 13 character display controlled by two rotary switches, four line select keys, a display freeze key (Mark), a waypoint mode key, a page slew key, and an alphanumeric keypad. The MODE switch selects the receiver operating mode, the DATA switch selects which parameters are to be displayed, and the keyboard is used to make parameter entries.

In addition to the basic position, velocity, and time displays, the CDU also provides status information on various display pages. Some of this information is the external interface configuration, satellite tracking status, estimated position error, age of satellite almanac, PTTI 1 pulse per second time difference, and the Built-In-Test (BIT) fault log data. Control functions

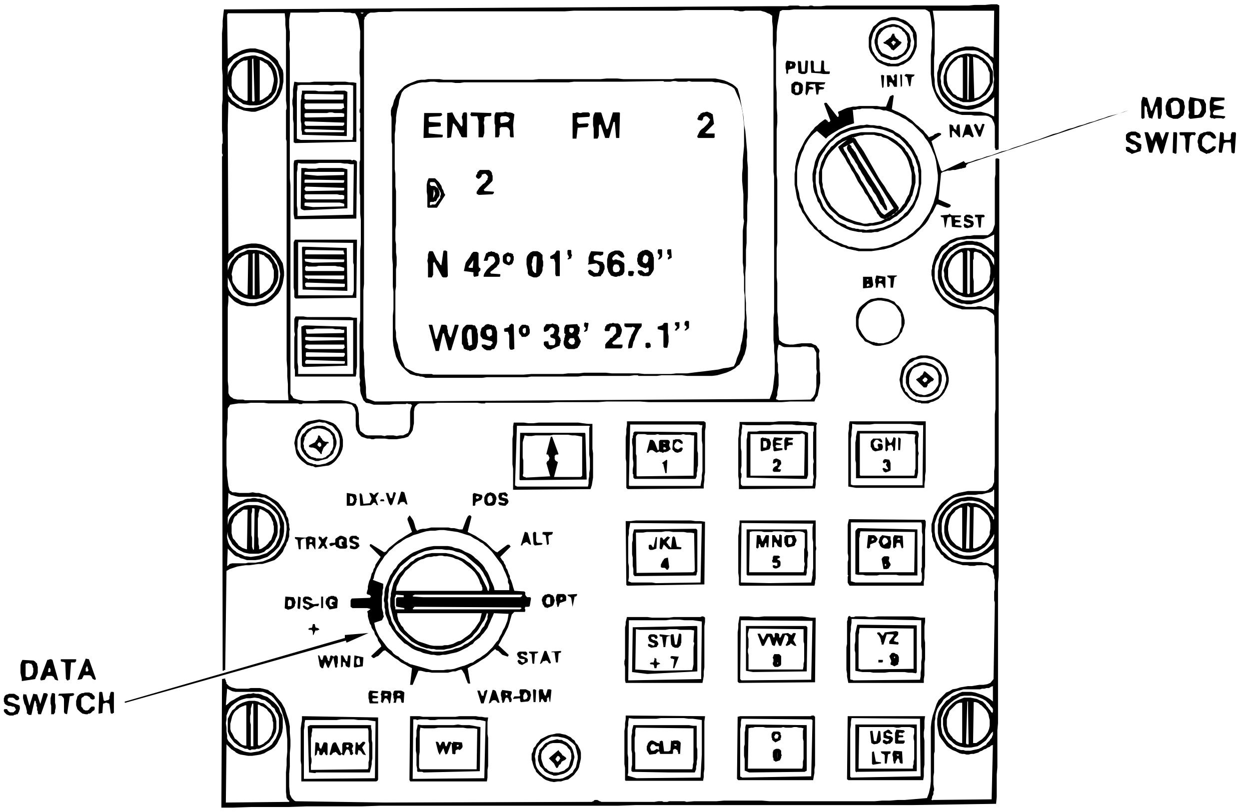


Figure 4-1. Example of a Dedicated CDU

include the selection of the lever arm source, flight instrument interface mode, and aiding sensor control.

4.2.3.1.2 Multiple Dedicated CDU Operation

Control and display for a GPS receiver may involve more than one dedicated CDU. The design of a GPS receiver may incorporate two dedicated CDU interfaces and may also provide a data link interface (e.g., MIL-STD-1553) that can also be utilized for control and display. However, only one interface should be able to control and manually initialize a GPS receiver at any given time. A master CDU can be designated by a software configuration connector strap as either a data bus or one of the dedicated CDUs. The master CDU is initially the "active" CDU when the receiver is powered up and may always regain control from another CDU if it has relinquished control to that unit. A designator indicating the current active CDU should be stored in non-volatile memory so that it will not change as a result of a accidental power outage. The active CDU has the sole responsibility for control and manual initialization and thus has sole responsibility for the following:

- Receiver Mode Commands
- Rendezvous Mode Selection

- Waypoint Activation
- Destination Selection
- Waypoint Definition
- Mark Definition
- Desired Track/Desired Vertical Angle Selection
- Altitude Hold Activation
- Stationary Mode Activation
- Flight Instrument Scaling
- Map Datum Selection
- Acquisition Uncertainty Selection

4.2.3.1.3 Multifunction CDU

A view of the front panel of a multifunction CDU, with a sample display, is shown in Figure 4-2. The CDU has an eight line, 22 character display controlled by standard and special function keys, full alphanumeric keypad, and eight line select keys. The CDU utilizes a menu driven approach for control, display, and data entry in lieu of the rotary switches of the dedicated CDU.

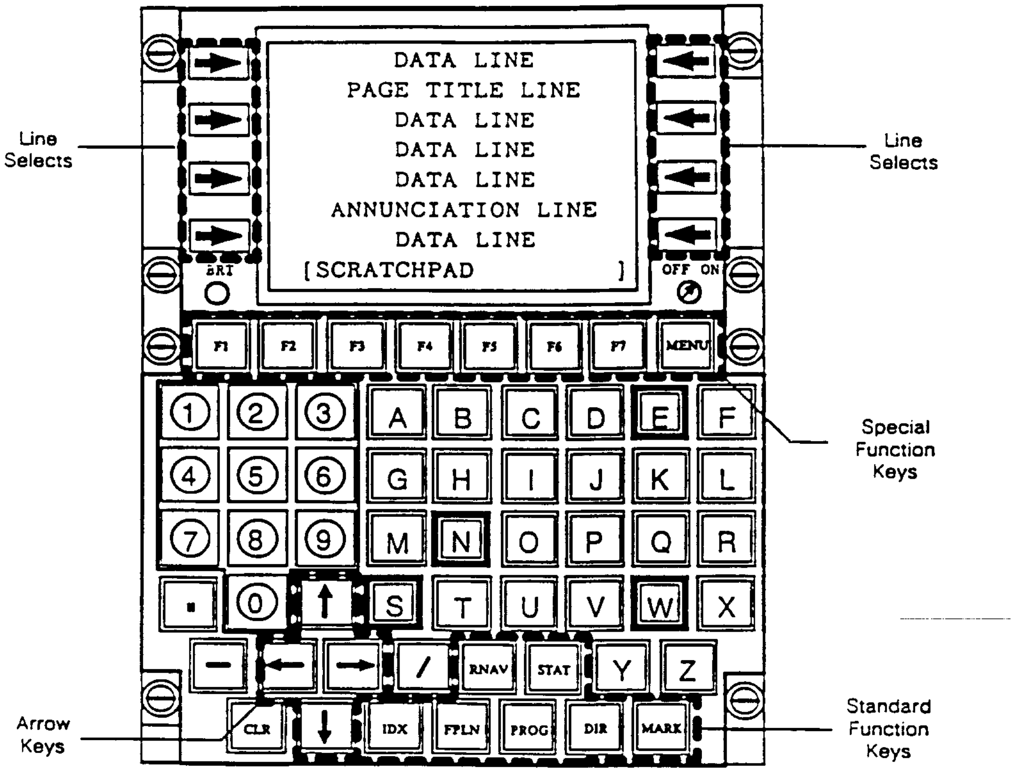


Figure 4-2. Example of a Multifunction CDU

The CDU includes enhanced area navigation software and a dual-redundant MIL-STD-1553 data bus. It is capable of operating as either a bus controller, backup bus controller, or remote terminal. The CDU can act as the MIL-STD-1553 bus controller and exchange data with the following equipment:

- GPS Receiver
- Attitude Heading Reference System (AHRS)
- Central Air Data Computer (CADC)
- Mission Data Loader (MDL)
- Two Additional CDU Systems

4.2.3.1.4 Multiple Multifunction CDU Operation

The CDU MIL-STD-1553 bus logic can be designed to support an installation of two or more CDUs. In multiple CDU operations, one CDU is the bus controller and the other(s) are remote terminals and backup bus controllers. If the active bus controller fails, then another CDU becomes the bus controller and no degradation in system performance occurs. The CDU can be designed such that in multi-CDU installations, any CDU can become the "active" CDU and all can have independent control of data display.

4.2.3.2 Data Loader System

A GPS receiver (and/or multifunction CDU) may have the capability to load relevant data over a data link from a Data Loader System (DLS). The primary function of the interface is to provide the ability to input initialization data from an external nonvolatile memory device. This is almost essential for GPS avionics systems that must be compatible with civil aviation and use a large International Civil Aviation Organization (ICAO) standard waypoint and navaid data base. A data loader may also be useful for storing navigation, status, or mission data collected during a mission. The DLS may be used to store and load the following:

- Waypoints and Flight Plans
- GPS Satellite Almanac Data
- GPS Satellite Health/Status Data
- Antenna Lever Arm Data
- Instrumentation Port Parameters
- SA/A-S Data
- Sensor Configuration Data

An example data loader system is shown in Figure 4-3. The system consists of a memory device and a read/write/interface unit. The example memory device is a plug-in cartridge that contains solid state memory, memory addressing circuitry, serial input/output converters, and an alkaline cell to power the memory for data retention purposes. Other memory devices such as magnetic tape cassettes and computer diskettes are also common. The read/write/interface unit is installed in the HV and often resembles a small tape deck in size and appearance. It contains the appropriate circuitry to read from and write to the memory device, and contains interface circuitry to send and receive data from the data link (e.g., MIL-STD-1553 or ARINC 429).

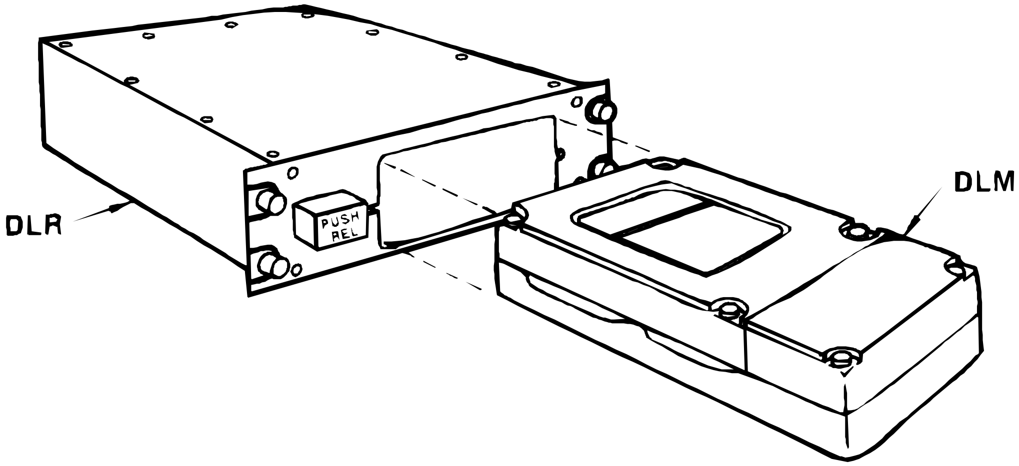


Figure 4-3. Example of a Data Loader System

4.2.3.3 Flight Instrument Interface Unit

Some GPS receiver designs will pass analog signals directly to the flight instruments, but many designs may have a digital-only output via an ARINC 429 interface. The reason for a digital-only design is the anticipation of all-digital flight instruments in the future. Aircraft with analog flight instruments may require a separate digital-to-analog converter to convert the digital data to the synchro, analog and discrete signals needed to drive these instruments.

As an example, the Signal Data Converter (SDC) unit, developed for the U.S. DoD, performs this function. In concept, the SDC process is simple; the SDC takes the digital ARINC 429 data stream and converts those parameters to analog signals that can be handled by analog flight instruments. Not all of the parameters can be used (e.g. waypoint, latitude, and longitude) since the analog flight instruments have no way of processing or displaying such data. Data which can be used by analog flight instruments include:

- Distance to Waypoint
- Waypoint Bearing
- Desired Track (or radial)
- Vertical/Horizontal Deviation From Selected Track (2-D or 3-D)
- Data Validity Discretes
- To/From Indication

The use of GPS for navigation in a military aircraft is often seen as a substitute for the Tactical Air Navigation (TACAN) system. Therefore, it may be desirable to use TACAN procedures with GPS, and it may also be desirable for the GPS displays to emulate the TACAN displays. The SDC includes the capability to function as a TACAN digital-to-analog converter by means of a simple discrete switch. This provides a simplified method for GPS access to the analog flight instruments, using the existing TACAN wiring path (i.e., replace the existing TACAN D-to-A with the SDC).

Since GPS is still a relatively new system, some of the TACAN system characteristics need to be considered. Identified below are GPS flight instrument display and procedures comparisons to TACAN and other radio navigation aids.

4.2.3.3.1 Deviation Scale Factor

With TACAN, a 2-dot horizontal deviation displacement represents 10 degrees off the required radial. An Instrument Landing System (ILS) Localizer has a 2-dot displacement of approximately 3 degrees (runway dependent). In the case of the U.S. DoD equipment, the GPS 2-dot displacement represents either 4 nmi, 1 nmi, 0.3 nmi linear displacement, or 3 degrees depending on the scale factor selected (Enroute, Terminal, Nonprecision Approach, or Approach respectively).

These GPS horizontal scale factors were generally derived from airway track keeping requirements for the various phases of flight. The Enroute scale factor was derived from the typical ±4 nmi U.S. National Air Space (NAS) Airway width. The Terminal scale factor was selected based on U.S. Air Force Instrument Flight Center flight testing. The Non-Precision Approach scale factor corresponds with U.S. FAA non-precision approach tolerance. The Approach scale factor simulates an ILS localizer display.

If 3-dimensional waypoints are used, then the U.S. DoD GPS receiver can present vertical deviation information. The vertical 2-dot deflections are 1000 ft, 500 ft and 200 ft linear displacement, and 0.7 degrees corresponding to the En Route, Terminal, Non-Precision Approach, and Approach scale factors respectively. The linear scale factors provide the opportunity to someday utilize GPS for vertical navigation in level flight. The Approach vertical scale factor simulates an ILS glideslope display.

4.2.3.3.2 TACAN and GPS Flight Procedural Differences

In the TO/FROM TACAN Navigation mode, the Omni Bearing Select (OBS) knob on the Horizontal Situation Indicator (HSI) allows the pilot to select the radial (to or from the current waypoint) along which he wishes to fly. As the knob is turned and the radial changes, the horizontal deviation bar swings to show the pilot whether he is left or right of that radial. In the case of TACAN, the OBS knob feeds back to the TACAN Digital-to-Analog Converter (DAC), where the left/right computation is carried out (see Figure 4-4). The deviation bar is driven by angular differences. The U.S. DoD SDC can mimic the TACAN DAC as shown in Figure 4-4.

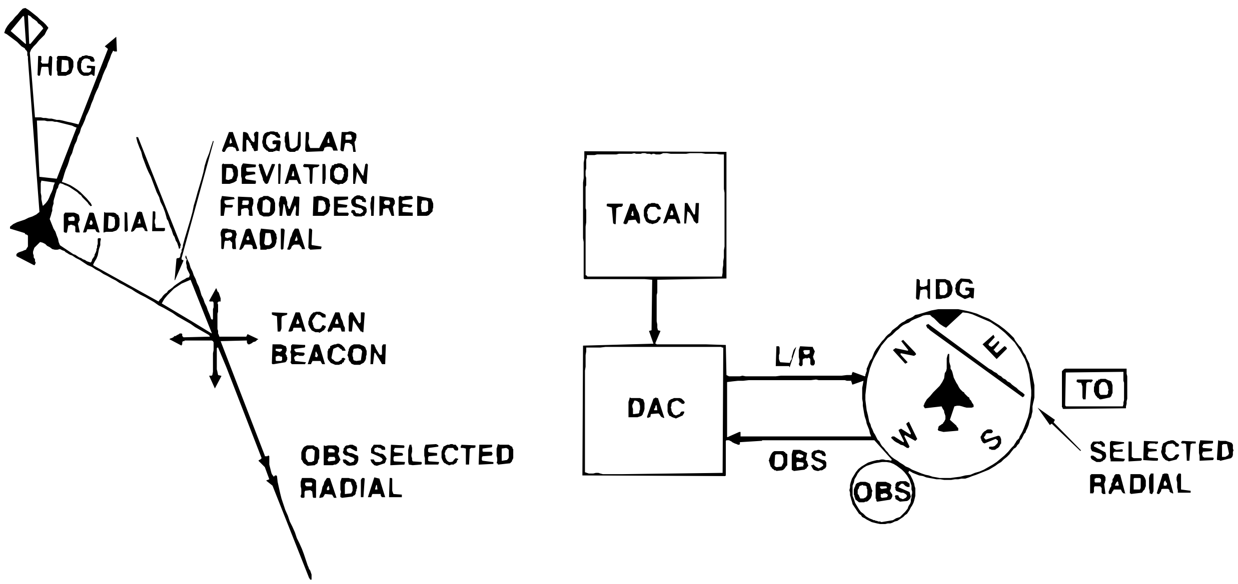


Figure 4-4. Flight Instruments and TACAN

In the case of U.S. DoD GPS receivers using GPS TO/FROM Navigation mode, the receiver is programmed with waypoint information which includes desired track. This can be analogous to selected TACAN station (waypoint) and OBS radial setting (desired track). The deviation bar deflection will be a function of linear distance (when not in approach mode) of the aircraft perpendicular to the desired track which was programmed in the receiver (see Figure 4-5). The SDC provides a desired track output synchro signal that can drive the HSI OBS to the appropriate radial setting. The pilot, however, can not turn the OBS knob to select a new GPS desired track (other similar products may choose to incorporate the OBS knob setting). The pilot wishing to change the desired track value must enter it into the CDU. The pilot alternatively can select the Direct-To navigation function to get a direct course to the waypoint.

Pilots generally steer magnetic headings. GPS is an inherently "true" system. One must therefore be careful that the SDC always has a designated magnetic or true heading source and the GPS receiver has knowledge of local magnetic variation, or assigned magnetic variation (in the case of Navaids used as waypoints).

4.2.3.4 Inertial Navigation Systems

A GPS receiver integrated with an Inertial Navigation Systems (INS) forms a particularly effective navigation system. The GPS receiver can compensate for the long-term drift of an INS and an INS can compensate for the short-term noise and relatively low data rate of a GPS receiver. (Additional discussion of GPS integration architectures is provided in Chapter 8).

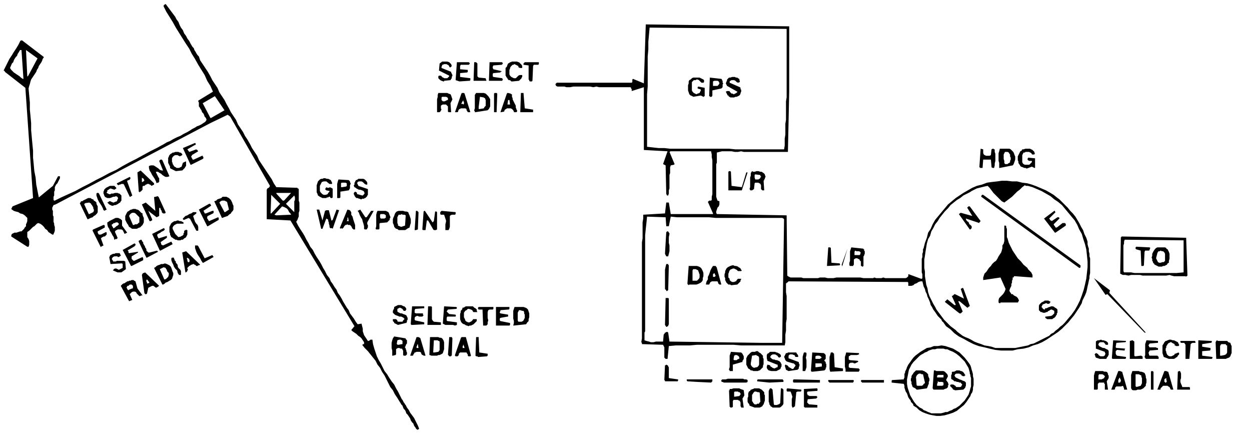


Figure 4-5. Flight Instruments and GPS

4.3 PRECISE TIME AND TIME INTERVAL INTERFACE

4.3.1 Introduction

GPS is becoming recognized as the primary time dissemination system for military and commercial applications. An example of a system which may use time transfer from GPS is the calibration of atomic clocks.

4.3.2 Precise Time Inputs

A time input is used to reduce the uncertainty of the receivers initial time estimate and thus reduce TTFF, or it may be used instead of a satellite in the navigation solution. The precise time input to a GPS receiver is accomplished by using a 1 pulse per second rate representing UTC one-second-rollover and a Binary Code Decimal (BCD) time code describing the pulse per second time from an atomic clock. The pulse input indicates the moment of the time to UTC, and the BCD time code identifies what time it was at the UTC one-second-rollover.

The MIL-STD-1553 PTTI Input Message time transfer mechanism uses the same time rollover pulse input. However, instead of labeling the time with a BCD time input, the HV supplies a PTTI input message via the MIL-STD-1553 MUX bus to label the time epoch.

4.3.3 Precise Time Outputs

The primary function of these outputs is to calibrate an atomic clock, or to support other systems that require precise time. The outputs are 1 pulse per second or 1 pulse per minute to indicate the one second or one minute rollover of UTC, and a BCD time code that indicates the time at the rollover epoch (Hours, Minutes, Seconds, Day of Year, Time Figure of Merit (TFOM)).

Another means of precise time transfer from the GPS receiver is to use the 1 pulse per second output in conjunction with the PTTI output message available on the MIL-STD-1553 multiplex bus.

4.4 ROLL/PITCH/HEADING/WATER-SPEED ANALOG INPUT INTERFACE

A shipborne receiver should be able to accept analog inputs of the ship's attitude and water speed in coarse and fine synchro format. The heading input signal can be used by the receiver to assist in satellite acquisition and tracking, and for relative course calculations. The roll/pitch input signal can be used by the receiver to compensate for antenna motion. The water speed input signal can be used by the receiver to aid in satellite acquisition and tracking, and for relative speed calculations.

4.5 INSTRUMENTATION PORT INTERFACE

GPS receivers typically have an interface for testing during development and manufacturing. If the configuration of this interface is documented and controlled, it may be useful for integration purposes. Several U.S. DoD GPS receivers have an instrumentation port interface. This interface can be used for some HV integration applications and for connection of test equipment used by maintenance and test activities. The interface is a full duplex RS-422 serial interface that can be connected to a Smart Buffer Box for test instrumentation purposes, or to an Intermediate Level Test Set for maintenance purposes.

4.6 RS-232 INTERFACE

RS-232 is a common interface typically used to interface between computer equipment. The PLGR includes a RS-232 2-way serial port. This port provides the capability to control the PLGR remotely, and to transfer data between PLGRs or between a PLGR and a computer. This interface can also be used for reprogramming PLGR operational software.

4.7 BAROMETRIC ALTIMETER INTERFACE

A variety of barometric altimeter devices output digitally-encoded pressure altitude, referenced to the geoid or Mean Sea Level (MSL), with a pressure reference of 1013.2 hectoPascals (formerly millibars). This is the same encoded altitude as is used in Mode C altitude reporting via an air traffic control radar beacon (IFF transponder). Some U.S. DoD GPS receivers have a compatible baro-altimeter input. It is a parallel interface which consists of ten signal leads and one signal return. The seven most significant bits are a Gray Code representation of the barometric altitude in feet, to the nearest 500 feet. The three least significant bits are a binary code which indicates the 100 foot increment within the 500 foot interval.

4.8 GPS INTERFACE OPTIONS

4.8.1 Introduction

Choice of interfaces for a GPS receiver are dependent on the system to which a GPS receiver shall be integrated, and are also dependent on the depth of the integration required. Alternative approaches to interfaces can be grouped as follows:

- Implement a new interface in an existing GPS receiver
- Redesign of HV systems to accommodate an existing GPS receiver
- Development of an interface box to adapt an existing GPS receiver to an existing HV system.

4.8.2 Implementing a New Interface in an Existing GPS Receiver

Good design of a GPS receiver allows the partitioning of the receiver portion and the interface requirements. Often this can be accomplished by using a separate processor to manage interfaces, thus buffering the performance of the GPS receiver portion from the individual demands of a platform interface. This gives the ability to add new interfaces with minimum impact on the majority of receiver software design. Given the flexibility of the software design, an existing GPS receiver can have a new interface card inserted into a spare card slot, or if an existing interface is not used, then the new interface card can be substituted for it. This choice is constrained by the hardware limitations of wiring, output pin availability, etc.

4.8.3 Redesign of HV Interfaces to Accommodate an Existing GPS Receiver

Redesign of the HV interfaces to accommodate the GPS receiver with its current interface is a possibility; however, it may not be considered practical unless major components of the HV can be changed at the same time. With GPS becoming available as a sensor (rather than an LRU with interfaces), embedded GPS receiver alternatives (e.g., embedded in an INS) should also be considered when systems are being replaced.

4.8.4 Separate Development of an Interface Box

One approach that can have minimal impact on both an existing GPS receiver and HV systems is the design of a separate "box" that performs the interface functions. This "box" would accept existing interface inputs and outputs of a GPS receiver and convert them to the inputs and outputs normally used by the HV systems. This approach still requires the HV system's software to be changed to accept another navigation input, and the issues of space, weight, and power for the new "box" must be addressed. Of importance is the impact on the data senescence caused by the additional time delay necessary for the "box" to convert the data.

CHAPTER 5: ANTENNA SUBSYSTEMS

5.1 INTRODUCTION

GPS users have different requirements for GPS system performance which demand a variety of antennas and antenna subsystems. There are three basic types of GPS antennas, a passive Fixed Radiation Pattern Antenna (FRPA), a FRPA with an integrated preamplifier, and a Controlled Radiation Pattern Antenna (CRPA). The requirement to drive a long cable run, with its associated signal loss between the antenna and the GPS receiver has resulted in a FRPA with an integrated amplifier. A CRPA is required to reduce the effects of RF interference which would otherwise jam the receiver's operation.

5.2 FRPA

5.2.1 General Characteristics

A FRPA has a fixed antenna radiation pattern which is only affected by the size and shape of the ground plane on which it is installed. As GPS antennas are typically narrow band the radiation pattern does not change over either the L1 or L2 bandwidth although due to the difference between the L1 and L2 wavelength there are significant differences in the radiation at the L1 and L2 frequencies.

Typical specifications for FRPAs include parameters for operating frequencies, impedance, Voltage Standing Wave Ratio (VSWR), radiation pattern, polarization, axial ratio and gain. These specifications impact receiver performance. The size, shape and weight of the FRPAs will vary with the application. A FRPA for an aircraft installation has a different form than a FRPA for a hand-held receiver. A number of FRPAs are discussed below. FRPAs are generally non-repairable units which require no adjustment over their lifetime. Passive FRPAs require no power. All FRPAs can be fitted with an external low noise amplifier should this be needed to overcome losses introduced by a long cable length. The amplifier will probably require a low power DC voltage.

An important parameter when selecting a GPS antenna is the gain. Gain is defined with respect to an isotropic radiator for circular polarization, expressed as dBic, and the sector of the sphere surrounding the antenna over which the gain can be maintained, expressed as the angle from the antenna boresight. (The boresight is the central axis of the antenna usually the direction of maximum gain).

To receive the signals from GPS satellites, which may be at any angle in the upper hemisphere, the gain must not drop below -5 dBic. In the case of an aircraft there is a significant problem of maintaining sufficient gain towards the satellites as the aircraft maneuvers through high angles of pitch and roll. Typically an aircraft's GPS antenna gain falls to -15 dBic below the azimuth plane, although a worst case gain of -20 dBic can be assumed.

5.2.2 FRPA Types

There are many types of GPS FRPA antenna. The simplest is a resonant monopole approximately 5 cms in length. However, as the monopole has a toroidal radiation pattern and is vertically polarized, it is not optimum for use with the circularly polarized GPS transmissions. Gain is very low, -40 dBic on boresight and peaking to approximately 0 dBic at 70° from boresight depending on the conductivity of the ground plane.

Spiral Helix antennas are useful for several receiver applications where a small antenna is required that is generally unaffected by the presence or absence of a ground plane. The antenna can be configured to be low profile, but is not conformal and is therefore not suitable for fast aircraft. The antenna is less sensitive to the influence of the ground plane than some other FRPAs and is capable of being mounted on non-conducting surfaces, making it suitable for a variety of applications from vehicles to handheld receivers. Typically the gain is better than -4 dBic from boresight to 80°. The antenna's mechanical layout and typical dimensions are shown in Figure 5-1.

The FRPA Bifilar Helix is designed for hand-held applications and is capable of being integrated into a broad category of ground vehicles in addition to its main application on the Precise Lightweight GPS Receiver (PLGR). The antenna is insensitive to ground plane and installation location. Streamlined outer shell can be added to enable the device to be used in medium dynamic, for instance helicopter applications. It provides a gain of not less than - 3 dBic over 80° angle from boresight. The antenna's mechanical layout and typical dimensions are shown in Figure 5-2.

To produce a conformal design for aircraft applications where minimal drag is required, a crossed slot or patch antenna can be used. The crossed slot is effectively four monopoles laid out at right angles with a suitable separation above the ground plane. Patches can take many formats. These antennas rely on the aircraft skin acting as a ground plane to achieve the required antenna performance. Gains of +2 dBic are typically achieved on boresight and, although the gain to circularly polarized radiation falls to -5 dBic at 90° (from boresight), the gain is sufficient to allow satellites to be tracked through medium dynamic aircraft maneuvers. Antennas can be made that are sensitive to L1 and L2 GPS frequencies. The mechanical layout and the dimensions of an example antenna are shown in Figure 5-3.

A special derivative of a FRPA crossed monopoles antenna is the FRPA Ground Plane. This special FRPA assembly (see Figure 5-4) is intended for shipborne mast applications where there is no ground plane. The assembly consists of a ground plane/mounting surface for the FRPA plus an environmentally sealed enclosure containing an integrated preamplifier. A derivation of the FRPA Ground Plane is employed for GPS Reference Stations in a differential system. In these applications a special choke ring is added to the antenna to reduce the gain in the direction of likely sources of multipath.

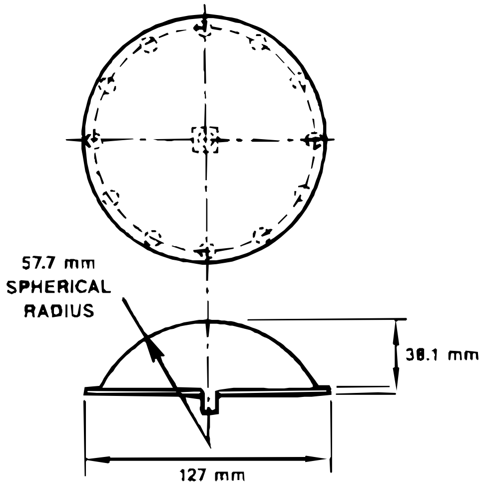


Figure 5-1. FRPA Spiral Helix

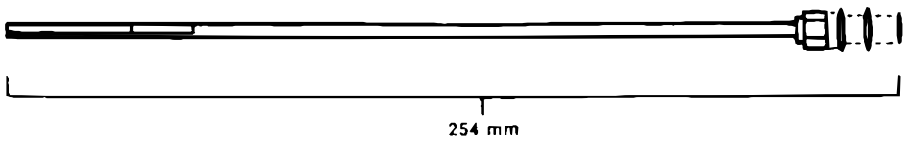


Figure 5-2. FRPA Bifilar Helix

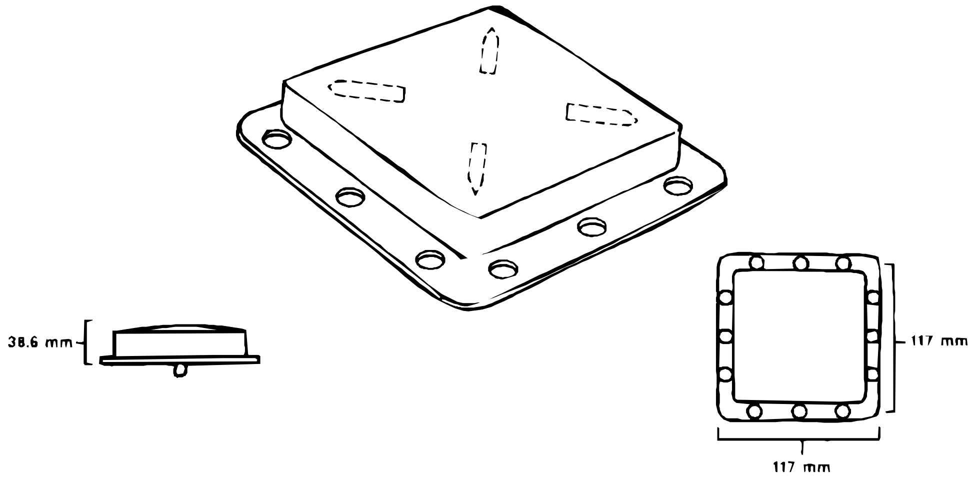


Figure 5-3. FRPA Crossed Monopoles

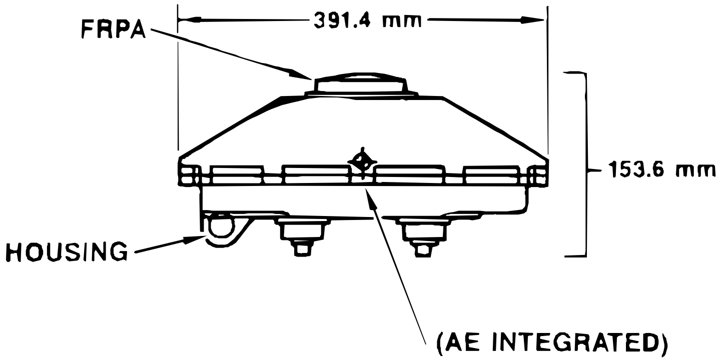


Figure 5-4. FRPA Ground Plane

5.3 CRPA Equipment

CRPAs have been shown to be the only effective means of protecting GPS receivers against multiple wideband jammers. A CRPA has two components: an Antenna Control Unit (ACU) and an antenna array. Current aircraft CRPA's typically have seven antenna elements in the array with seven associated processing channels. CRPAs under development for missile may use only four or five elements.

The antenna array is composed of antenna elements which may be of any of the above FRPA types. However the vehicle environment significantly limits the choice. In the case of aircraft the array has to be conformal and is therefore usually made up of patch or crossed dipole antennas. The antenna elements are spaced at approximately half wavelength separation, at the shortest operational wavelength. It is essential for optimum operation of the CRPA that all the antenna elements in the array have omnidirectional performance with constant gain characteristics over as large a sector as possible.

The ACU controls the array's radiation pattern by adjusting the gains and phase from each antenna. First generation ACU employed analogue electronics with some digital control. Newer equipment digitizes the receiver signal in a similar manner to that used in a GPS receiver. The ACU contains a series of amplifiers and gain control systems for each channel, a set of weights that make up a beam former and a microprocessor and associated electronics that contains the control algorithm and drive the weights in the beamformer. Each weight is a phase shifter with gain control. The phase shift was initially performed by analogue components but it is now cost effective to employ digital multiplier circuits. The receiver signal is downconverted to near baseband and sampled into inphase and quadrature components. By adjusting the gain and sign of each component a 360 degree range is achieved.

As the GPS signal is below the thermal noise in the transmission bandwidth, any signal detected above the thermal noise level can be considered to be harmful to GPS operation. Initially the array's radiation pattern is set to omnidirectional, by adjusting the gain and phase in the ACU. Whenever a jamming signal is detected, the gain and phase of the beamformer is adjusted to form a null in the radiation pattern in the direction of the jammer with the result to cancel the effect of the jammer.

A CRPA has one less degree of freedom than the number of elements (N), allowing N-1 independent jamming sources to be cancelled.

CHAPTER 6: SERVICE COVERAGE, SERVICE AVAILABILITY, AND SERVICE RELIABILITY; SATELLITE SELECTION CRITERIA AND FIGURE OF MERIT DESCRIPTION

6.1 SERVICE COVERAGE, SERVICE AVAILABILITY, AND SERVICE RELIABILITY

This section describes the minimum performance an authorized user can expect to obtain from PPS receiver which is designed and operated in accordance with "Technical Characteristics of the Navstar GPS". Performance is specified in terms of minimum performance standards for each performance parameter. Each standard includes a definition of applicable conditions and constraints. The information provided in this section is derived and extracted from "The Global Positioning System (GPS) SPS Performance Specification", dated November 5, 1993, published by the U.S. DoD. Although the GPS SPS Performance Specification is directed toward SPS users of GPS, the specified performance of the system with respect to service coverage, service availability, and service reliability is the same for PPS users.

The data and associated statements provided in this chapter represent conservative performance expectations, based upon extensive observations of the system. The performance standards are limited to GPS Control Segment and Satellite contributions to the PPS signal-in-space characteristics and their effects on the position solution. The standards do not include enhancements or degradations to this service that might be provided by the UE or local environment. Examples of possible enhancements include altitude aiding, clock aiding, differential corrections, or integrity algorithms. Examples of possible local degradations include multipath, jamming, terrain masking, or receiver errors.

6.1.1 Parameter Definitions

The three parameters defined below are service coverage, service availability, and service reliability. These definitions and the relationships between them are different from traditional definitions of similar parameters. A dependent relationship is defined to exist between these performance parameters. Each successive layer of performance definitions are conditioned on the preceding layers. That is, coverage must be provided before the service may be considered available and it must be available before it can support service reliability requirements.

Service coverage is defined as the percentage of time over a specified interval that a sufficient number of satellites are above a specified mask angle and provide an acceptable position solution geometry at any point on or near the earth.

GPS coverage is viewed somewhat differently than coverage for existing terrestrial positioning systems. Traditionally coverage has been viewed as the surface area or volume in which a system may be operated. Since a terrestrial system's beacons are fixed, coverage does not change as a function of time. Since the GPS concept relies upon the dynamics of a satellite constellation, coverage must take into consideration a time dependency. GPS coverage is by definition intended to be global. GPS coverage is viewed alternatively as the percentage of time over a time interval that a user, anywhere in the world and at any time, can see a sufficient number of satellites to generate a position solution. Constraints are placed upon satellite visibility in terms of mask angle and geometry, to minimize the possibility of a GPS receiver generating a marginal position solution. Coverage characteristics over any given region vary slightly over time, due primarily to small shifts in satellite orbits.

Since GPS is a space-based system, coverage is defined as a function of each satellite's antenna beamwidth. The GPS satellite antenna's nominal beamwidth is approximately 28 degrees. If a user on the Earth's surface were to view a satellite which is just above the local horizon, the user could elevate from that location to an altitude of approximately 200 kilometers above the Earth's surface before effectively losing that satellite's signal. This condition defines the maximum altitude associated with the term "on or near the Earth."

Service availability is defined as the percentage of time over a specified time interval that a sufficient number of satellites are transmitting a usable ranging signal within view of any point on or near the earth, given that coverage is provided.

Just because a satellite is operational does not mean that it is currently transmitting a usable GPS ranging signal. Satellites will, on occasion, be removed temporarily from service for routine maintenance. As a result, the number of satellites actually transmitting usable ranging signals will vary over time. Service availability is the measure of how GPS coverage deviates from nominal conditions due to the temporary removal of satellites from service. This measurement represents the percentage of time that coverage is provided by those satellites which are transmitting usable ranging signals to generate a position solution. Variations in service availability are a function of which satellites are removed from service, the length of the service outage, and where on the globe a user is located in relation to any resulting outage patterns.

Service reliability is defined as the percentage of time over a specified time interval that the instantaneous predictable horizontal error is maintained within the normal accuracy distribution at any point on or near the earth, given that coverage is provided and the service is available.

GPS can be used anywhere in the world. A failure in a system with such global coverage may affect a large percentage of the globe. A natural concern about using GPS is whether or not it provides a satisfactory level of service reliability. Service reliability as it is used in a GPS context is somewhat more restrictive than the classical definition, which includes times that the service is available as well as when it is performing within specified tolerances. GPS service reliability is viewed as a measure only of how well GPS maintains horizontal errors within the normal predictable PPS horizontal accuracy distribution. 100% service reliability is provided when the horizontal error remains within the normal accuracy distribution within the conditions specified for coverage and service availability. Periods where the service does not provide a sufficient number of satellites or adequate geometry to support position solution generation are assessed against the coverage service availability performance standard.

6.1.2 Service Coverage Characteristics

This section defines the GPS coverage standards, GPS constellation design objectives, and the characteristics of GPS coverage which are expected with a 24 satellite operational constellation. The user is provided with general information concerning how coverage will vary over time on a global basis, and a worst-case projection of coverage on a regional basis. The data provided in the discussion is based upon a global assessment of grid points spaced equally, approximately 111 kilometers apart, every 30 seconds over a 24 hour period.

6.1.2.1 Service Coverage Standards

GPS Service will be provided in accordance with the coverage standards presented in Table 6-1.

Table 6-1. Service Coverage Standards

Coverage Standard	Conditions and Constraints
≥99.9% global average	· Probability of 4 or more satellites in view over any 24 hour interval, averaged over the globe · 4 satellites must provide PDOP of 6 or less · 5° mask angle with no obscure · Standard is predicated on 24 operational satellites, as the constellation is defined in the almanac
≥96.9% at worst-case point	· Probability of 4 or more satellites in view over any 24 hour interval, for the worst-case point on the globe · 4 satellites must provide PDOP of 6 or less · 5° mask angle with no obscure · Standard is predicated on 24 operational satellites, as the constellation is defined in the almanac

6.1.2.2 The GPS 24-Satellite Constellation

The 24 satellite constellation is designed to optimize global coverage over a wide range of operational conditions. Specific constellation design objectives are listed below:

- Provide continuous global coverage with specified geometry and mask angle constraints.

- Minimize coverage sensitivity to expected satellite orbital drift characteristics.

- Mitigate the effects on service availability of removing any one satellite from service.

Several factors affect GPS coverage. These factors must be taken into consideration in the constellation design. The factors are:

- The difference between the planned orbit and the orbit actually achieved during the launch and orbit insertion process,
- Orbit variation dynamics, and
- Frequency and efficiency of satellite station-keeping maneuvers.

6.1.2.3 Expected Service Coverage Characteristics

Proper support of the first design objective (from above) requires that at least four satellites are continuously in view with an acceptable geometry and mask angle anywhere in the world. An implication of this requirement is that most of the time significantly more than four satellites will be visible. As shown in Figure 6-1, eight satellites will be visible on average for any location in the world, over 24 hours. Very seldom will a user see only four satellites when all 24 satellites are providing usable ranging signals. If the 24 satellites in the GPS constellation were all launched with no deviations into their planned orbits, and no drift were allowed, the constellation would provide virtually 100% (0.99999714) four satellite coverage with a PDOP constraint of six.

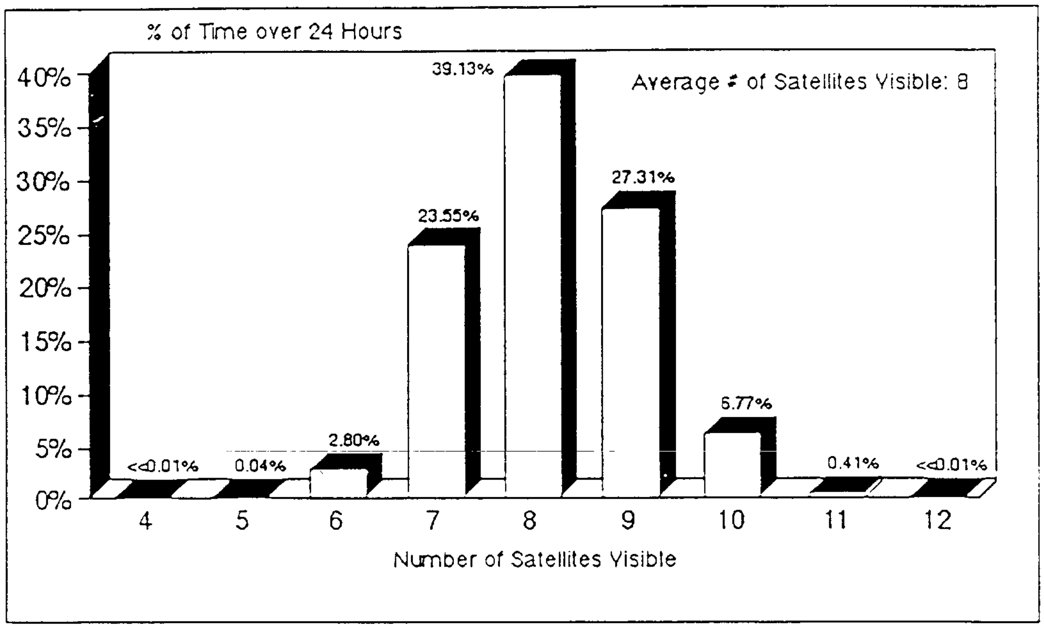


Figure 6-1. Satellite Global Visibility Profile

Unfortunately, variations in final orbits based upon launch uncertainties and routine drift do occur. The second design objective is supported by evaluating how changes in each satellite's orbital elements affect nominal coverage characteristics. Bounds are applied to orbital element deviation from the nominal orbit to ensure that constellation coverage does not degrade beyond allowed limits. Degraded coverage areas drift and change slightly in shape over time, but their average number and duration will remain approximately constant for a given constellation. Changes in the number of satellites or significant shifts in satellite orbits, however, can dramatically change the attributes of degraded coverage areas.

Given a 24 satellite constellation, GPS will provide 100% four and five satellite coverage without a PDOP constraint (but with a mask angle of 5 degrees), and six satellite coverage greater than 99.9% of the time. However, four satellite coverage with a PDOP constraint of 6 can drop as low as 99.9%, with a worst-case dispersion of the 24 satellites with respect to their nominal orbits. Even in this event, most users will experience continuous coverage. A few isolated locations may experience four-satellite coverage as low as 96.9%, with a PDOP constraint of 6 and a mask angle of 5 degrees.

Satisfaction of the third design objective requires the ability to remove any individual satellite from the constellation, and still be able to provide as close to continuous global coverage as is practical. Satisfaction of this objective requires that at least five satellites be in view almost continuously. As shown in Figure 6-1, this is the case with the 24 satellite constellation design. Although an explicit requirement is not established to ensure that multiple combinations of satellites provide adequate solution geometry at any given time, most of the time at least two and usually more combinations of four satellites will support a Position Dilution of Precision (PDOP) constraint of 6 or less.

6.1.3 Service Availability Characteristics

This section defines the GPS availability standards and expected regional and global service availability characteristics. The user is provided with information concerning GPS service availability patterns on a global and regional basis. Service availability varies slightly over time, due to routine satellite maintenance requirements. Note that the regional service availability values provided below are based upon a global grid point spacing of approximately 111 x 111 kilometers, with 30 second intervals over 24 hours.

Service availability is described in two basic parts. The first part concerns the variation in service availability as a function of temporarily removing a number and specific combination of satellites from service. The second part of the assessment applies service availability variation characteristics to an operational scenario.

6.1.3.1 Service Availability Standards

GPS service will be provided in accordance with the availability standards specified in Table 6-2.

6.1.3.2 Satellite Outage Effects on Service Availability

Service availability varies predominantly as a function of the number and distribution of satellite service outages. With a 24 satellite constellation, the permutations and combinations of satellite service outages are rather large. Normally, no more than three satellites will be removed from service over any 24 hour interval. This ground rule bounds the problem to an analysis of the effects of removing each satellite and all combinations of two and three satellites from service for no more than 24 hours. The results of the analysis are summarized in Table 6-3.

Table 6-2. Service Availability Standards

Service Availability Standard	**Conditions and Constraints**
^{3}99.85% global average	· Conditioned on coverage standard · Standard based on a typical 24 hour interval, averaged over the globe · Typical 24 hour interval defined using averaging period of 30 days
^{3}99.16% single point average	· Conditioned on coverage standard · Standard based on a typical 24 hour interval, for the worst-case point on the globe · Typical 24 hour interval defined using averaging period of 30 days
^{3}95.87% global average on worst-case day	· Conditioned on coverage standard · Standard represents a worst-case 24 hour interval,averaged over the globe
^{3}83.92% at worst-case point on worst-case day	· Conditioned on coverage standard · Standard based on a worst-case 24 hour interval, for the worst-case point on the globe

6.1.3.3 Expected Service Availability Characteristics

Table 6-3 defines what service availability characteristics will be like for a given satellite outage condition. Service availability projections over time may be generated by applying the information in Table 6-3 to expected satellite control operations scenarios. A satellite control operations scenario is based upon a conservative estimate of satellite maintenance activity frequency and duration. Satellite maintenance actions requiring service downtime include periodic cesium frequency standard maintenance, station keeping maneuvers to maintain orbits within tolerances, and responses to component failures. Given current routine maintenance requirements and component failure expectations, generally three, and no more than four satellites should be removed from service over any 30 day period. Once a satellite is removed from service, it is assumed that it will be down for no more than 24 hours.

The first service availability scenario to be defined represents a worst-case 30 day period. A summary of this scenario is provided in Table 6-4. The scenario is considered to be worst case from two perspectives: it includes a day with three satellites removed from service, and it includes a total of four satellite-down days. The three satellite-down scenario is based upon the simultaneous removal of two satellites for routine maintenance, accompanied with a component failure on a third satellite. Worst case global service availability on a day with three satellites removed from service is 95.87%; the associated worst case regional service availability is 83.92%. The resulting 30-day service availability values range from 99.85% to 99.99%, depending on which satellites make up the four which

Table 6-3. Service Availability as a Function of
Specified Satellite Outage Conditions

Satellite Temporary Outage Condition	Global Average Service Availability	Worst Regional Service Availability
No Satellites Out:	100.00%	100.00%
ONE SATELLITE OUT FOR MAINTENANCE OR REPAIR		
Least Impacting Satellite Out:	99.98%	99.17%
Average Satellite Out:	99.93%	97.79%
Most Impacting Satellite Out:	99.83%	97.63%
TWO SATELLITES OUT FOR MAINTENANCE OR REPAIR		
Least Impacting 2 Satellites Out:	99.93%	98.21%
Average 2 Satellites Out:	99.64%	95.71%
Most Impacting 2 Satellites Out:	98.85%	91.08%
THREE SATELLITES OUT FOR MAINTENANCE OR REPAIR		
Least Impacting 3 Satellites Out:	99.89%	97.13%
Average 3 Satellites Out:	99.03%	93.38%
Most Impacting 3 Satellites Out:	95.87%	83.92%

Table 6-4. Example of 3-Day Global Service Availability
with Component Failure on Worst Day

Ops Scenario Condition	Best Case	Average Case	Worst Case
1 Day - 3 Satellites Down	99.89%	99.03%	95.87%
1 Day - 1 Satellite Down	99.98%	99.93%	99.83%
28 Days - No Satellites Down	100.00%	100.00%	100.00%
Average Daily Availability	99.99%	99.97%	99.85%

experience downtime. The service availability service standard was established based upon this scenario, to ensure that the system can support standard compliance.

The second service availability scenario is shown in Table 6-5, and represents what may be considered to be a more common 30 day interval. In this scenario, three satellites were removed from service for up to 24 hours, each on separate days. Typical satellite maintenance operations are conducted on one satellite at a time, which means that the removal of two satellites for maintenance at the same time will be a rare occurrence.

Global service availability on a day where the worst case satellite is removed from service is 99.85%; the associated worst case regional service availability is 97.63%. The resulting 30-day service availability values do not change much between the best and worst cases, with the worst case value being 99.98%.

Table 6-5. Example of 30-Day Global Service Availability
without Component Failure

Ops Scenario Condition	**Best Case**	**Average Case**	**Worst Case**
3 Days - 1 Satellite Down	99.98%	99.93%	99.85%
27 Days - No Satellites Down	100.00%	100.00%	100.00%
Average Daily Availability	99.99%	99.99%	99.98%

6.1.4 Service Reliability Characteristics

This section defines conservative expectations for GPS service reliability performance. These expectations are based upon observed accuracy characteristics, the GPS service failure history to date, long-term failure rate projections, and current system failure response capabilities. The user is provided with information which indicates expected failure rates and their effects on a global and regional basis.

6.1.4.1 Service Reliability Standards

GPS service will be provided in accordance with the reliability standards presented in Table 6-6.

Table 6-6. Service Reliability Standards

Service Reliability	**Conditions and Constraints**
≥99.97% global average	· Conditioned on coverage and service availability standards · Standard based on a measurement interval of one year; average of daily values over the globe · Standard predicated on a maximum of 18 hours of major service failure behavior over the sample interval
≥99.79% single point average	· Conditioned on coverage and service availability standards · Standard based on a measurement interval of one year; average of daily values from the worst-case point on the globe · Standard based on a maximum of 18 hours of major service failure behavior over the sample interval

6.1.4.2 GPS Service Failure Characteristics

A GPS service failure is defined as an excursion of unpredictable magnitude of the horizontal position solution due to a control segment or satellite fault which is unrelated to the normal predictable long-term PPS horizontal accuracy distribution. A GPS service failure is characterized by a large single-satellite range error which is unrelated to the normal long-term PPS range error distribution.

The characteristics of a service failure and the factors which affect service reliability are listed below. Each is discussed in more detail in the following sections.

- Ranging signal failure frequency
- Failure duration
- Failure magnitude and behavior
- Distribution of user population around the globe
- Probability that the failed satellite is used in the position solution
- Effect that the failure has on the position solution, given the failed satellite's contribution to solution geometry and the receiver's response to the failure condition.

6.1.4.3 Failure Frequency Estimate

The GPS satellite positioning service failure history over the past several years indicates a very low service failure rate (excluding Block I satellites). However, when a service failure does occur, it can result in extremely large position and/or velocity errors. This behavior will typically persist until action is taken to remedy the problem.

Based upon an historical assessment of Block II satellite and Control Segment failure characteristics, GPS should experience no more than three major service failures per year (excluding Block I satellites). This failure rate estimate is conservative - expectations are on the order of one per year, based upon projected navigation payload component reliabilities and the assumption that action will be taken to switch redundancy configurations if early indications of an imminent failure are detected. An allocation of three per year allows for a possible increase in service failures as the Block II satellites reach the end of their operational life expectancy.

6.1.4.4 Failure Duration Estimate

The duration of a failure is a function of the following factors:

- Control Segment monitor station coverage
- Control Segment monitor station, communications and Master Control Station availability
- Master Control Station failure detection efficiency and timeline
- Timeline for correcting the problem or terminating the failed satellite's service.

The combination of these factors results in a conservative system operator response timeline on the order of no more than six hours. In most cases the response to a failure will be much more prompt, but with any complex system such as the Control Segment, allowances must be made for varying system resource status and operational conditions.

6.1.4.5 Failure Magnitude and Behavior

GPS is designed to be fault tolerant - most potential failures are either caught before they manifest themselves, or their effects are compensated for by the system. The only failures to which the system seems susceptible are of two types:

- Insidious, long-term (day or more to become evident) performance deviations, or
- Catastrophic, almost instantaneous failures

Insidious failures do not propagate very quickly - failures of this type experienced to date have not affected the GPS ability to support accuracy performance standards. Insidious failures are typically due to a problem in the ephemeris state estimation process.

Catastrophic failures are due almost exclusively to satellite frequency generation hardware failures. These failures in general result in very rapid ranging error growth - range errors can grow to several thousand metres in a very short period of time. Typically, a failure of this type will begin with a phase jump of indeterminate magnitude, followed by a large ramp or increased noise consistent with the behavior of a quartz oscillator.

6.1.4.6 User Global Distribution and Failure Visibility

For the purposes of reliability performance standard definition, the effect of a service failure is not weighted based upon user distribution - a uniform distribution of users over the globe is assumed.

Given a maximum failure duration of six hours, approximately 63% of the Earth's surface will have a failed satellite in view for some portion of the failure. The average amount of time that the failed satellite will be in view for those locations which can see it is approximately three hours.

6.1.4.7 Satellite Use in the Position Solution

Given a 24 satellite constellation, an average of eight satellites will be in view of any user on or near the Earth. The satellite visibility distribution for the nominal 24 satellite constellation is shown in Figure 6-1. With all satellites weighted equally, the probability of a failed satellite being in the position solution of any user located within the failure visibility region is 50%. Equal weighting is considered to be a reasonable assumption for use in global reliability computations. However, in the worst-case individual site computation it must be assumed that the receiver is tracking and using the failed satellite for the duration of the satellite visibility window.

6.1.4.8 Failure Effect on Position Solution

Given the nature of catastrophic failures, it must be assumed that the inclusion of the satellite in the position solution will induce a service reliability failure independent of the satellite's geometric contribution. Some receivers will be capable of detecting and rejecting large instantaneous changes in a range residual which are indicative of a major service failure. The minimum receiver represented in the Signal Specification is not however, required to have this capability. For the purposes of service reliability standard definition, it must be assumed that if the receiver is capable of tracking the failed satellite and it supports the nominal position solution geometry, the receiver will use it in the position solution.

6.1.4.9 Expected Service Reliability Characteristics

When the system is performing nominally and the receiver design meets the minimum usage conditions established in Section 2.2 of the Signal Specification, predictable horizontal error will never reach the service reliability threshold. Service reliability on those days where GPS does not experience a major service failure will be 100%.

The estimated maximum of three major service failures per year, coupled with a maximum duration of six hours each, yields a maximum of 18 service failure hours per year. The worst-case site on the globe will be the place where all 18 service failure hours are observed and the failed satellites are used in the position solution. For this worst case condition, the daily average service reliability over a one year period will be no worse than 99.79%. The equivalent global daily average will be no worse than 99.97%.

6.1.5 Additional Commentary

(The following commentary is not derived from the GPS SPS Performance Standard.) It should be noted that several criteria used as conditions and constraints in the performance standards may not be applicable to many user applications. As examples, the coverage standard is based upon 24 operational satellites, a four-satellite position solution, a PDOP of 6 or less, and a 5 degree mask angle; the service availability standard is based on a "normal" operating scenario; and the service reliability standard is based on the assumption that the user does not perform integrity checking.

6.1.5.1 24 Operational Satellites and Service Availability

The assumption of 24 operational satellites may be optimistic rather than conservative. In the long term, the GPS constellation will be in a continuous cycle of satellite end-of-life failures and corresponding launch of replacements. It is expected that three to four satellites will reach end-of-life each year, based on experience with the Block I satellites and considering design improvements to the Block II satellites. This means that service coverage can change every few months, although end-of-life failures can be anticipated to some degree and some launches can be made prior to the actual failure. A number of studies have been conducted to determine the probability of a specific number of satellites in service at any given time, including some studies conducted for the U.S. DoD to help determine satellite replenishment strategies. One such study gives the long-term probabilities for the number of GPS satellites operational any given time.

In most cases, a satellite vacancy from the full constellation of 24 satellites will result in reduced service coverage. For convenience, the lack of a four satellite positioning solution or a condition where PDOP > 6 will be termed an "outage". In general, the number of outages, individual durations of outages, and areas affected by outages will increase with each additional vacancy from the constellation. As long as the U.S. can maintain 21 or more satellites on orbit, and worst-case situations can be avoided, the service coverage is likely to remain between 99% and 100%. Table 6-8 below gives some representative values of service coverage for a 24-Satellite constellation with "typical" deviations from the nominal orbit positions. During the worst-case three-satellite-failure condition, the worst location in the world may experience as low as 86% average positioning availability over a 24 hour period, while the best location may still experience 100% availability.

Table 6-7. Probability of Operational Satellites

Number of Satellites	State Probability	Cumulative Probability
24	0.72	0.72
23	0.17	0.89
22	0.064	0.954
21	0.026	0.980
20	0.0116	0.9916
19	0.0064	0.9980

Table 6-8. Service Coverage of a Typical 24-Satellite Constellation

Number of Satellites	Best Global Service Coverage	Average Global Service Coverage	Worst Global Service Coverage
23	100.00%	99.99%	99.97%
22	100.00%	99.93%	99.61%
21	99.98%	99.69%	97.69%
20	99.97%	99.05%	94.75%

As suggested above, there are several options the U.S. DoD may employ to minimize the impact of reduced service coverage. Such options include launches in anticipation of satellite end-of-life failures, planning normal maintenance to minimize service availability impact, deferring normal maintenance, and even minor rephasing of certain satellites in the constellation. In this respect, the standards quoted above for service availability under "normal" operating conditions have some flexibility to compensate for reduced service coverage and still maintain a high composite availability of a position solution.

6.1.5.2 PDOP Less Than Six

PPS users are much less sensitive to large values of DOP than SPS users. Many PPS users will have sufficient position accuracy using GPS as a stand-alone system even if PDOP is greater than six. For example, for navigation missions, horizontal position accuracy is usually a more appropriate measure than PDOP. As a general rule of thumb, a PDOP of six is typically equivalent to an HDOP of four (although PDOP obviously contains a vertical component which can vary). This means that an approximate worst case PPS error for "normal" horizontal variations would be around 160 metres (assuming a three-sigma URE of 20 for all satellites and a maximum geometric effect of 2 X HDOP = 8). Many PPS users of GPS can navigate safely with a horizontal position accuracy of a kilometer or more, for example, ships in open ocean and aircraft enroute at altitude, and can therefore tolerate much higher values of HDOP (and PDOP). Therefore, "areas of reduced accuracy" is often a more appropriate term than "outage" for conditions of large PDOP, since the accuracy of the position solution may be reduced but still adequate for the mission requirements.

This suggests that the user should evaluate the performance standards with respect to the anticipated mission requirements. If the mission requirements are significantly different than the constraints used to develop the performance standards, an independent assessment of service coverage via computer simulations may be warranted. One method of determining the real-time effect of prevailing range errors and satellite geometry is calculation of a FOM described in paragraph 6.3 below. The user can then reduce the uncertainty associated with global averages and long-term statistics by comparing the current accuracy estimate to the mission accuracy requirements and thereby significantly improve the probability of success of the mission.

Most military GPS users will have to contend with the possibility of GPS "outages," due to hostile local conditions, for example, terrain masking or intentional jamming. One solution for some applications is an integrated navigation system. For example, if a GPS receiver is integrated with an inertial navigation unit, an intermittent GPS solution can be sufficient to maintain continuous high-accuracy positioning. For other applications, vertical aiding can be used as a pseudo-satellite to enhance availability, or differential GPS can be used to minimize range errors and correspondingly reduce sensitivity to DOP.

6.1.5.3 Four-Satellite Solution and Five-Degree Mask Angle

In effect, the performance standards are based on a "model" GPS receiver that calculates a four-satellite PVT solution and is constrained by a five-degree mask angle. In evaluating the impacts of these constraints, the user must consider the type of equipment that he is actually employing. Significant gains in service coverage can be achieved by the use of aiding, for example, from an altitude source or precision clock. Similarly, significant gains in service coverage can be expected if the satellite mask angle actually implemented by the receiver and GPS antenna is lower than five degrees. Correspondingly, a higher mask angle will reduce service coverage. In the event that the actual receiver differs significantly from the "model" receiver used to develop the standards, an independent assessment of service coverage may be advisable by means of computer simulations.

6.1.5.4 Integrity Checking

The service reliability concept defined here is closely related to the NATO concept of integrity. Consequently, user equipment that employs integrity checking algorithms may be able to detect the majority of "service failures" and continue to maintain a valid position solution by choosing a set of satellites which excludes the one experiencing the service failure. Various integrity monitoring algorithms have been developed by the civil aviation community which are well documented in open technical literature, and most receiver manufacturers are familiar with them. Most of these algorithms are based on the principle of a consistency check using additional range measurements and developing multiple solutions for comparison purposes (aiding measurements can be included). However, when such algorithms are employed, a minimum of five measurements are usually required, rather than the four required for a minimum position solution. Therefore, the overall system availability is likely to be determined by the availability of the integrity decision, rather than the availability of the navigation solution. Fortunately, the availability of an integrity decision based on PPS measurements is extremely high, since PPS is not subject to SA "noise" which can make SPS integrity decisions more difficult. Table 6-9 gives some results for the availability of an integrity decision from a recent study of a PPS integrity algorithm for military aviation which included pressure altimeter aiding. The results are based on a five-degree mask angle and a 556 metre position error threshold, suitable to protect the accuracy required for a nonprecision approach. The probability of detecting a service failure for this algorithm is 0.999, which when multiplied by the probability of occurrence of a service failure yields an overall level of integrity in excess of 0.99999.

Table 6-9. Availability of the Integrity Decision

Number of Satellites	Best Global Availability	Average Global Availability	Worst Global Availability
24	N/A	100.000%	N/A
23	99.998%	99.985%	99.965%
22	99.993%	99.866%	99.391%
21	99.94 %	99.37 %	97.55 %

Again, an assessment of the mission requirements is warranted to determine the integrity threshold, probability of residual "service failures", and duration of integrity "outages" that can be tolerated. For example, an application that involves safety of life may require that a position solution be declared invalid unless a positive confirmation of integrity is achieved. In contrast, a weapons delivery system might allow the position solution to be valid unless a negative assertion of integrity is determined, with the residual loss of integrity considered a minor overall detriment to weapon effectiveness when compared to the alternative loss of weapon availability.

6.1.5.5 Summary of the Commentary

If there are significant differences from the "model" receiver implied by the performance standards, different constraints applicable to the application, or different mission requirements, an independent assessment of the performance standards or similar parameters is probably warranted via computer simulation. In addition, real-time integrity checking and calculation of a figure-of-merit can significantly reduce the uncertainty associated with global averages and long-term statistics, and significantly improve the probability of success of a given military mission.

6.2 Satellite Selection Criteria

6.2.1 Introduction

The criteria used for satellite selection is a very important factor in GPS receiver design. Different receivers perform satellite selection using different algorithms. The important satellite criteria to be considered include:

a. Satellite health
b. Geometric dilution of precision
c. User range accuracy
d. Elevation angle
e. Availability of external aids.

6.2.2 Satellite Health

The NAV msg contains satellite health information for all the satellites in the GPS satellite constellation. Each satellite broadcasts health summaries for all (up to 32) GPS satellites, in page 25 of subframes 4 and 5. Each summary consists of 1 bit indicating the health of the NAV msg and 5 bits indicating the health of the satellite signals. (Refer to "Technical Characteristics of the Navstar GPS" or ICD-GPS-200PR for additional details). A satellite should never be used in a Nav-solution if its Nav-message is indicated to be unhealthy. If the NAV msg health is good, the five-bit signal status message should be compared against valid operating modes for the receiver to determine if the satellite can be used. For example, a P-code receiver could use a satellite broadcasting L1 only, if an ionospheric model can be used instead of dual frequency measurements to make the ionospheric corrections.

The NAV msg also contains a health message in subframe 1 which indicates the health of the broadcasting satellite. Since the data in subframes 4 and 5 are updated less frequently than subframe 1, subframe 1 may be used to indicate short-term health problems or may be updated before subframes 4 and 5. Therefore, after a satellite is acquired, the health data in subframe 1 should also be checked to determine if the satellite can be used.

6.2.3 Geometric Dilution of Precision

As described previously in Chapters 2 and 3, GDOP is an important factor in determining the accuracy of the position (or time) solution. The combination of satellites which gives the lowest DOP value will provide the most accurate solution, assuming that all satellites have the same pseudorange error. Depending on the user mission, best PDOP, HDOP, or TDOP can be used as a satellite selection criterion.

6.2.4 User Range Accuracy

Each satellite broadcasts a user range accuracy (URA) value in subframe 1 of the NAV msg. URA is a prediction of the pseudorange accuracy obtainable from the satellite signal in space. URA is based on recent historical data and is therefore most accurate immediately following an upload. It does not include the UEE and therefore does not include ionospheric compensation error if the ionospheric model is used instead of dual frequency measurements. These additional errors should be added to URA for the best estimate of pseudorange accuracy, especially if the receiver is capable of performing dual frequency measurements on some satellites and must use an ionospheric model for others. (Refer to "Technical Characteristics of the Navstar GPS" or ICD-GPS-200PR for a more detailed explanation of URA.) URA can be used in conjunction with DOP to choose the best combination of satellites when the satellites have significantly different pseudorange errors. This is done by using URA as a weighting factor in the covariance matrix for user position and clock bias errors. Since URA is a prediction, it is not a guarantee of range accuracy, however, it can be used to help deselect satellites with known large pseudorange errors.

6.2.5 Satellite Elevation Angle

Selecting satellites by computing a minimum DOP will favor the use of satellites at low elevation angles. However, signals from satellites at a low elevation angle must travel a longer distance through the ionosphere and troposphere than signals from higher angles. They will therefore incur additional pseudorange error due to ionospheric and tropospheric delay. Many receivers will not use satellites below an arbitrary elevation angle. Five degrees is a typical lower limit. This also helps to reduce multipath problems.

6.2.6 External Aids

When an external aid is available to the GPS receiver, it can be incorporated into the satellite selection algorithm. It can be incorporated as a fixed mode of operation, an optional mode of operation when only three satellites are visible, or it can be treated as an additional "satellite" to be selected when the best combination of satellites includes the aid. Decision logic for the first two cases is relatively simple. If the aid is treated as an additional satellite, the expected error and geometry must be modelled and included in the satellite selection algorithm. For example, mean sea level (MSL) aiding can be considered to be equivalent to a satellite at the center of the earth with a UERE on the order of a typical satellite (6-7 metres). Other aiding schemes can be more complex, depending on the complexity of the integration, error model, and equivalent geometry. Barometric altimeter aiding should be treated with extra caution. Barometric altimeters are excellent devices for measuring pressure altitude, but pressure altitude can vary widely and non-linearly from geometric altitude. The resulting vertical errors should be modeled carefully since the errors can depend on meteorological conditions and vehicle dynamics. For additional discussion of GPS aids, refer to Chapter 7.

6.3 FIGURE OF MERIT (FOM)

A FOM is an indicator of receiver positioning or time accuracy which may be displayed to the operator or communicated to an integrated system. A FOM may be either a qualitative or quantitative measure, depending on the accuracy and integrity of the data used to calculate the FOM. In general, a FOM is not suitable for making integrity decisions where safety of life is concerned. However, a qualitative FOM may be perfectly suitable for integrity decisions regarding unmanned missions. (Refer to Chapter 12 for additional discussion of integrity.)

A FOM is typically calculated as the root-sum-square of the estimated errors contributing to the solution accuracy. Example criteria include:

a. GPS receiver state (e.g., carrier tracking, code tracking, acquisition)
b. Carrier to noise ratio
c. Satellite geometry (DOP value)
d. Satellite range accuracy (URA value)
e. Ionospheric measurement or modelling error
f. Receiver aiding used
g. Kalman filter error estimates.

The resultant FOM can be presented as a numerical value, for example from 1 to 9, where 1 indicates the best navigation performance. It can also be presented directly as an error estimate in metres, at a specified probability level, or even as a simple pass/fail indication. A time figure of merit (TFOM) can also be calculated to indicate the quality of the precise time information available from the GPS receiver via the PTTI interface (see paragraph 4.3.3). Table 6-10 gives the FOM and TFOM numerical assignments and equivalent estimated errors for the Rockwell-Collins family of receivers developed for the GPS JPO.

Table 6-10. FOM/TFOM Numerical Values and Estimated Errors

FOM/TFOM	**Estimated Position Error (EPE, metres)**	**Estimated Time Error (ETE, UTC)**
0	Not Used	(Note 1)
1	EPE < 25	ETE £ 1 ns
2	25 < EPE £ 50	1 ns < ETE £ 10 ns
3	50 < EPE £ 75	10 ns < ETE £ 100 ns
4	75 < EPE £ 100	100 ns < ETE £ 1 µs
5	100 < EPE £ 200	1 µs < ETE £ 10 µs
6	200 < EPE £ 500	10 µs < ETE £ 100 µs
7	500 < EPE £ 1000	100 µs < ETE £ 1 ms
8	1000 < EPE £ 5000	1 ms < ETE £ 10 ms
9	EPE > 5000	10 ms < ETE, or Fault
10 to 14	Not Used	Not Used
15	Not Used	ETE Not Available

Note 1: External time source indicates proper/normal operation by TFOM = 0.

CHAPTER 7: AIDING OPTIONS FOR A GPS RECEIVER

7.1 TYPES OF AIDING

Aiding a GPS receiver is done by incorporating inputs from external sources and is performed to enhance the following operations:

a. Acquisition of initial satellite signals,
b. Translate the navigation solution to a position in the HV other than the GPS antenna,
c. Replace a satellite measurement in case of limited visibility or bad satellite geometry,
d. Maintain satellite tracking by increasing the tolerance of the GPS receiver to interference, jamming or high HV dynamics.

Figure 7-1 illustrates some options. It should be noted that these are options and that not all GPS receivers presently have the capabilities described.

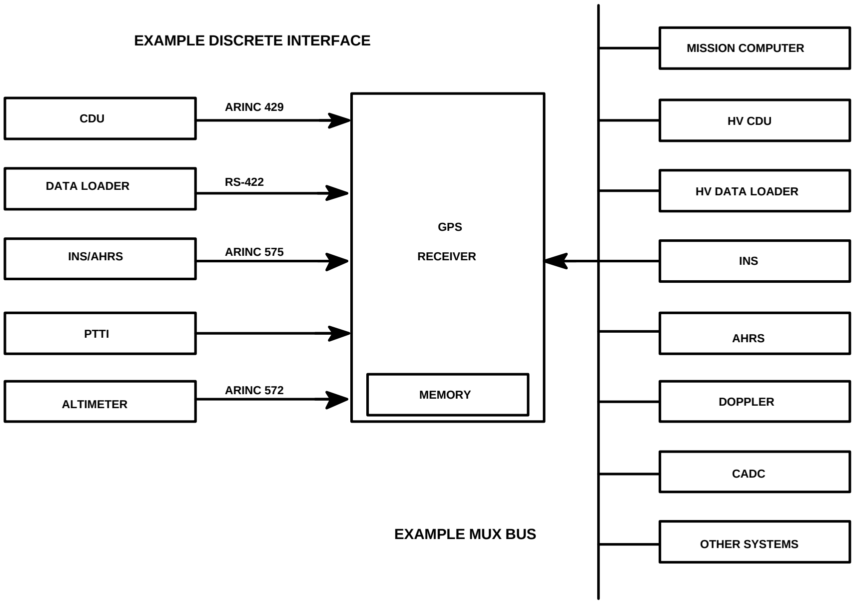


Figure 7-1. Aiding Options for a GPS Receiver

7.2 AIDING DURING INITIAL ACQUISITION

7.2.1 Position and Velocity Aiding

When a GPS receiver is first initialized for operation, approximate position and velocity of the receiver are required to minimize satellite acquisition time. The accuracy requirement of the U.S. DoD program for position is < 100 km of actual receiver location, and for velocity is < 100 m/s of actual receiver velocity, to ensure that satellite acquisition is within specification.

7.2.2 Time Aiding

Time aiding can be used during the initialization process, similar to position and velocity data. The time accuracy requirement is < 20 seconds relative to UTC. This is to ensure that satellite acquisition time is within specification.

Time aiding, if sufficiently accurate, can also be used to enable a direct P(Y)-code acquisition without first acquiring the C/A-code. This type of time aiding is relevant to HVs such as submarines where minimum exposure time of the GPS antenna on the ocean surface is of prime importance. An atomic time standard is one way to enable direct P(Y)-code acquisition.

7.2.3 Almanac Data

Normal satellite acquisition requires the availability of a current satellite almanac, stored in the receiver memory. If there are no significant changes in the satellite constellation, then the almanac is valid for several weeks.

If no stored or valid satellite almanac data are available, the GPS receiver starts to search the sky attempting to locate and lock onto any satellite in view. Depending on the receiver search strategy and on the actual satellite constellation, this process may take 15-60 minutes. When one satellite is being tracked, the receiver can download and read the almanac information about all the other satellites in the constellation.

7.2.4 Effect On TTFF

Dependent on the type of integration (position, velocity and time) aiding data to the GPS receiver during the initialization process are provided as follows:

a. Manually by the operator via the GPS CDU or HV CDU,
b. Automatically from INS/AHRS, PTTI or the HV mission computer (via 1553-bus),
c. Default by using the shut-down values stored in the receiver memory.

Initial acquisition performance can be expressed by the TTFF. In general terms, the TTFF is the time from when the receiver attempts to track the satellite signals until a navigation solution is determined. Knowing the position and velocity of the receiver, current time, and the positions of the satellites will all help to reduce the TTFF. Conversely, a lack of reasonably accurate knowledge of any of these parameters will increase the TTFF. The amount of increase is dependent on the particular quantity and level of uncertainty.

7.3 AIDING TO TRANSLATE NAVIGATION SOLUTION

The navigation solution of an unaided GPS receiver is referenced to its antenna position. An aided GPS receiver can reference its navigation solution to another location. For example, the GPS navigation state can be resolved at the IMU instrument axes center in the case of an INS. To perform the calculations, the receiver needs to be aided with attitude information and a lever arm vector.

The attitude information in the form of roll, pitch and heading is provided in most cases by an INS or AHRS. A GPS receiver usually does all internal calculations in ECEF before carrying out any coordinate transformations. Using latitude and longitude in conjunction with attitude, the transformation between the GPS ECEF navigation frame and the HV body frame can be determined. Onboard ships, attitude aiding is also used to compensate for antenna motion and, together with water speed information, to do relative course and speed calculations.

A lever arm vector is provided to the GPS receiver as a vector between the GPS antenna and the HV reference point. If attitude aiding is removed from the GPS receiver, the navigation solution should revert back to the GPS antenna location. Often, more than one set of lever arm corrections may be stored in the GPS receiver. This is useful for installations having more than one INS aiding source or, in the case of big ships, where position and/or velocity information for different locations onboard may be of interest. However, only one attitude aiding source should be used by the GPS receiver at any one time. Hence the propagated navigation solution will only incorporate the one set of lever arm corrections applicable to the particular aiding source that is providing aiding data to the GPS receiver. Should the aiding source be changed, the lever arm corrections will change accordingly.

7.4 AIDING TO REPLACE A SATELLITE MEASUREMENT

During normal receiver operations, four satellite measurements are required inputs to solve the equations for position (U_x, U_y, U_z) and clock offset Dt. In case of limited satellite visibility or poor satellite geometry, one or more of the four satellite inputs may be replaced by inputs from an external aiding source.

When the GPS receiver is shipborne, or has barometric altimeter aiding or has a known height, then only three satellites are needed. Additional aiding by a precise clock can supplement the measurements in a two-satellite situation.

7.4.1 Clock Aiding

A GPS receiver uses its own internal clock or may use a more accurate external clock as time reference. If only three (instead of four) satellites are available, then the GPS receiver can assume that its time reference is correct (Dt = known) and treat the three available satellite range measurements as actual ranges instead of pseudoranges. In this case, the accuracy of the position derived from the pseudorange measurements will correspond to the equivalent time reference error.

If the GPS receiver clock or the external clock can be monitored during a previous period in which the receiver navigates with four satellites, then the clock phase bias and drift can be calculated. The resulting corrections for clock errors can be used to provide very accurate GPS time during a satellite outage and an accurate GPS position can be maintained for several minutes.

The method of using a clock instead of a satellite is not recommended as a permanent solution, but rather to help the GPS receiver operate during short periods when only a limited set of satellites is available. A GPS receiver should be capable of receiving (and providing) precise time via a dedicated PTTI interface or via the 1553 -bus.

7.4.2 Altitude Aiding

Similar to the clock aiding discussed in the previous paragraph, an airborne GPS receiver can use a barometric altimeter as aiding to replace a satellite measurement. Long-term altimeter errors are calibrated during periods of four satellite operation. Subsequently, when less than four satellites are being tracked, the calibrated baro-altimeter data are used as a known U_z-value in the 4 unknowns of (U_x, U_y, U_z) and Dt. Conceptually, the barometric altitude added to the earth radius provides a range measurement from a satellite with position at the center of the earth. An accurate GPS position can be maintained for as long as the estimated baro altitude errors are valid. Since the barometric altitude errors are generally slowly varying, both in time and distance, reasonable position accuracy can usually be maintained for 10-15 minutes, or within a radius of roughly 10 nmi of the position of the last 4 satellite solution. A gradual loss of position accuracy, especially in the vertical channel, can be expected. Depending on the algorithm used to compute altitude from pressure, the loss of accuracy may be hastened by altitude changes in a nonstandard atmosphere, particularly if no temperature compensation is used.

7.5 AIDING TO MAINTAIN SATELLITE TRACK

In normal receiver operation, the code and carrier tracking loops are both being tracked in phase lock. There is a symbiosis between the code and carrier tracking loops where each loop aids the other. In a high jamming environment, the receiver may lose its ability to track the carrier. Subsequent accelerations will cause the carrier frequency of the received GPS signal to vary due to a change in the Doppler shift. The Doppler shift of the frequency of the received carrier signal is proportional to the relative velocity of the receiver with respect to the satellite along the line-of-sight from the receiver to the satellite.

Without some type of information to indicate this change in frequency, the center frequency of the receiver's replicated code signal will be different from the frequency of the actual received signal, which may then cause loss of code track as well.

A receiver may be able to maintain code track in this case even while losing carrier track if it is aided with velocity. The primary function of aiding in this degraded mode of operation is to maintain code-loop tracking. The velocity data replaces the carrier tracking loop output as the source for code tracking loop aiding. Possible sources of velocity include INS, AHRS, and Doppler navigation systems. Requirements on the accuracy of the velocity will determine the allowable amounts of senescence, synchronization error, and aiding source absolute error under varying dynamic conditions. For example, higher dynamics will generally mean tighter restrictions on data senescence, which in turn can mean higher aiding rates. Typical accuracy requirements on the aiding velocity in order to maintain code track when the carrier is lost are on the order of 2-3 m/second.

CHAPTER 8: POSSIBLE INTEGRATIONS OF GPS

8.1 INTRODUCTION

There are two ways to achieve integration with GPS: aiding which results in a hybrid or blended solution and aiding which results in a GPS solution. Implementations can range from a GPS receiver coupled with an external sensors such as an altimeter or a time aiding source, to integration with a navigation system. Examples of navigation systems include an INS, an AHRS, or a Doppler Radar Navigation Systems (DRNS).

GPS integrated with a navigation system provides the flexibility to have the navigation solution determined by the GPS receiver, by the host navigation system, or by a combination of the two. The GPS receiver can be aided by the host navigation system and provide the blended solution, or the navigation system may process GPS data to form the combined navigation solution. Another alternative is to have a central processor separate from the receiver or host navigation system, receiving data from both the GPS and host system and producing the blended solution. This last case essentially treats both the GPS receiver and host navigation system as sensors. The GPS receiver may reside on a card that is embedded into the host navigation system box so that the receiver physically becomes part of the host navigation system.

The benefits of integrating GPS with other navigation systems are significant and diverse. Basically, each system may have important shortcomings when used in a stand-alone mode, although together they can be integrated to mitigate most of these liabilities. An INS, AHRS, or DRNS, for example, is subject to an ever growing drift in position accuracy caused by various instrument error sources that cannot be eliminated in manufacturing, calibration or alignment. Other INS shortcomings include somewhat lengthy static alignment period or, alternatively, continuous operation in a powered alert status. Furthermore, a high quality INS can be a complex electro-mechanical device with significant risk of component failure. Additional shortcomings of Doppler systems include the reliance on an external heading input to form a navigation solution. Mission or flight critical implementations of these navigation systems require substantial redundancy in installation to detect, isolate, and recover from such failures for fail-safe operational performance.

A stand-alone GPS has its shortcomings as well. GPS is somewhat vulnerable to loss of signals due to RF interference, antenna shadowing, aircraft attitude maneuvers, or other causes. Receiver solution update rates may be fairly slow; i.e., in the 1 Hz region due to the complex processing of the radio frequency signals into a position or velocity solution. A 1 Hz update rate may be sufficient for most navigation applications, however, some avionics systems and weapons require much higher rates.

GPS used in conjunction with an aiding source can solve some or all of these limitations, depending on the aiding source used. An aiding source such as an altimeter or a precise time source can be substituted for a temporarily masked satellite. An INS, for example, can provide dynamic aiding data to the receiver that can be used to propagate the GPS solution during satellite outages and to aid in reacquisition of lost satellite signals. Basically, the marriage is between a short term, precise aiding source and the very long term, stable GPS reference.

8.2 MISSION REQUIREMENTS

The level of integration will largely depend on the particular mission requirements for navigation data accuracy and availability. Navigation system designers therefore need to clearly examine the mission requirements before deciding on the level of GPS integration necessary to adequately support military operations. Sample considerations that drive an integration design are listed below.

a. Navigation accuracy - What position, velocity and/or time accuracy are required from the navigation solution supported by GPS? GPS accuracy can be improved through the use of DGPS if proper host and support equipment is in-place (see Chapter 10).

b. Availability of navigation solution - What are the maximum HV dynamics for which the GPS set must navigate continuously with the highest level of accuracy? Is the user required to navigate accurately in a high interference or jamming environment? Sensor aiding data can greatly improve GPS availability under adverse conditions.

c. Reacquisition of GPS signal - How soon after any satellite signal interruption must GPS regain full navigation accuracy? How long can GPS interruption be accepted without measurable degradation of system performance? Reacquisition can be improved by other sensors as a rough initialization for initial GPS signal acquisition as well as for rapid reacquisition should signals temporarily be lost.

d. Sensor calibration - Is calibration of other navigation sensors by GPS required in order to maintain a high quality navigation during GPS outages? Does GPS have to provide INS platform misalignment error estimates to a quality that could support inflight INS alignment? Is management of multiple sensor output required for fault tolerance? GPS and other navigation sensors provide dissimilar redundancy for detecting hard and soft failures in either system.

e. Output rate of navigation solutions - The GPS receiver navigation solution output rate may be limited. If a higher output rate is required, the integration may require the GPS receiver to aid the INS, or for the GPS and navigation system data to be combined in an external navigation processor instead of GPS being used as the primary navigation source.

f. Modes of operation - Will the GPS receiver be required to operate as a primary or sole means of navigation and/or as a sensor to an INS, DRNS, or mission computer? The intended use of GPS greatly affects the integra tion strategy under signal loss or failure conditions.

8.3 INTEGRATION ARCHITECTURES

When requirements are well understood, the integration design has to address: (1) the selection of GPS and other equipment, (2) the selection of data transfer and interfaces and (3) the selection of a software concept.

There are essentially five architectures for integrating GPS in a system navigation solution. The resulting system architecture for GPS integration will be one of these basic structures as discussed in the following. There is a clear distinction in the potential performance available from the stand-alone receiver (see 8.3.1) and the aided/integrated configuration (see 8.3.2 to 8.3.4). However, the differences between the performance realized in the aided/integrated configurations may be small unless the mission computer makes aggressive use of GPS inputs.

8.3.1 GPS Stand-Alone/Baro/Clock Aided

The GPS stand-alone configuration (see Figure 8-1) shows a GPS receiver with inputs from an antenna set and options for barometric altimeter and clock aiding. The receiver outputs can drive any CDU or (analog) instrument that may be required.

This configuration would be used primarily for operation in low-dynamics. The user must be willing to accept reacquisition times of up to two minutes or more if the receiver loses lock because of jamming or dynamics.

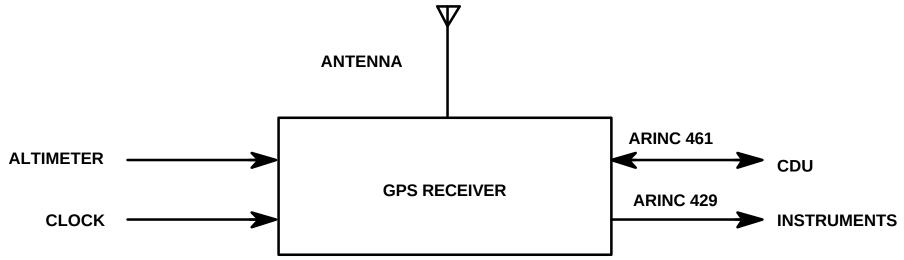


Figure 8-1. GPS Stand-alone Configuration

A barometric altimeter or an external clock are aiding options to coast the receiver through short periods when visible satellites are less than four. Especially for a low-dynamic environment, a barometric altimeter, can be very cost effective. The GPS receiver clock or a typical external clock can have drift rates that vary widely, from 10^{-10} s/s to 10^{-7} s/s. Thus, position error could grow to 100 m (95%) in a few seconds.

An atomic clock with a stability of 10^{-13} s/s will keep the GPS receiver within a 100 m (95%) position error for several minutes.

8.3.2 GPS/INS Integrations

The GPS INS-aided configuration (see Figure 8-2) is useful for medium to high dynamics applications. GPS receives INS sensor data from either a serial (e.g., ARINC 429) or multiplex (e.g., MIL-STD-1553) data port. Output is provided through the ARINC 461 and 429 databus port to the CDU and instruments. The GPS receiver may also provide position and velocity data to the INS. For older INS's in particular, there may not be an existing interface that will take data from a GPS receiver. This situation is often encountered when retrofitting GPS to vehicles that have been in service for a number of years. For integrating these systems with GPS, either the INS firmware must be modified to accommodate GPS data, or the GPS receiver must accept the INS data, or the GPS/INS integration must occur in a separate processor that accepts data from both the INS and GPS. In the last two cases, the INS continues to run free inertial, open loop with no feedback from the navigation processor if one is used.

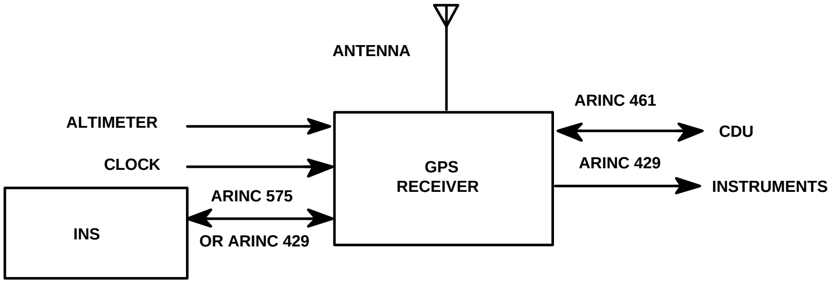


Figure 8-2. GPS INS-aided Configuration

If the INS solution can be updated by GPS, and is taken as the system navigation solution, it will have an accuracy similar to GPS whenever GPS is available. If the GPS data is used to estimate the major error sources that affect INS position, then if GPS becomes unavailable, the INS accuracy will degrade at a reduced rate when compared to the free inertial INS position error growth rate. Barometric altimeter and clock aiding may also be available but is not necessary in the INS-aided mode.

As discussed in paragraph 9.4.2.1, these are different levels of GPS/INS integration. The simplest is referred to as "loosely coupled", where the GPS receiver processes pseudorange and deltarange to produce geodetic position and velocity, which is then used by the INS. In this case, the INS is unaffected by the satellite geometry implicit in the GPS solution. However, if the receiver tracks less than four satellites, it may not be able to produce a geodetic solution, causing the INS to lose aiding by the GPS. A more complex GPS/INS integration is called "tightly coupled" where the INS uses pseudorange and/or deltarange measurements to correct its navigation solution. This implementation is more robust in that it can continue to correct INS errors to some degree even when there are less than four satellites being tracked. A major consideration to using tightly coupled integrations with current systems is that the pseudoranges and deltaranges corrected for SA are classified.

8.3.3 GPS and Mission Computer/Databus Emulator

The GPS configuration with mission computer/databus emulator (see Figure 8-3) is a means to provide the equivalent of 1553 bus operation in a vehicle that does not have a 1553-bus. It uses the mission computer (or sometimes a smart CDU) to emulate the ARINC 575 or 429 interface to GPS, as well as to control the interfaces to other navigation sensors. The main penalty in comparison to a 1553 architecture is the limited data transfer rate of the ARINC interfaces and the increased complexity of mission computer functions required to support data formatting and transfer among the different sensors.

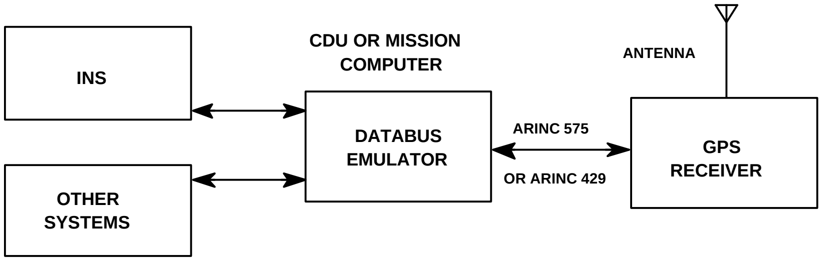


Figure 8-3. Configuration with Mission Computer/Databus Emulator

Examples of other systems to be integrated with GPS in this configuration are a doppler radar (velocity) combined with an AHRS. An AHRS is similar to an INS except that only HV attitude, attitude rates, heading and acceleration are available (no position). The quality of its output information is lower than that of a conventional INS. However, an integrated GPS/AHRS may become a direct replacement for a high quality INS. The estimated cost of an integrated GPS/AHRS is less than one-half that of a stand-alone INS. Additionally, yearly maintenance costs are expected to be one-third that of an INS.

8.3.4 GPS in a 1553 Databus Configuration

A GPS receiver includes a highly evolved set of interfaces to external systems. One such interface is the high-speed databus MIL-STD-1553 (see Figure 8-4). The 1553 databus may be used by high-dynamic, high-performance HVs to quickly transfer data between an external system and the GPS receiver.

Although a GPS receiver usually can only receive and transmit a limited number of well defined 1553 bus data blocks, the number of options is still large. Nevertheless, an integration cannot change the data blocks input to or output from a given GPS on the 1553 bus to meet its particular need. The only option is to program the 1553 bus controller to convert message formats as required for GPS and other remote terminals to communicate successfully.

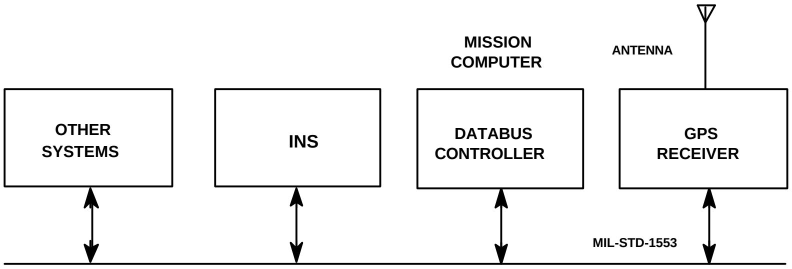


Figure 8-4. GPS in 1553 Databus Configuration

8.3.5 Embedded GPS

The previous sections essentially address integrations of physically separate GPS receivers and other sensors. GPS may also be integrated into other systems by embedding the receiver into the host system (eg., within an INS, DRNS, mission computer, CDU, etc). For these cases, the embedded system has the benefits of tight coupling as described in paragraph 8.3.2.

8.4 GPS AND TRANSIT/OMEGA/LORAN-C

Some hybrid systems have been developed that use the best data available from each of GPS, Transit and Omega. Navigation system measurements from all three systems can be integrated to generate an optimum system solution. If four GPS satellites are available and PDOP is within limits, the Transit and Omega measurement data are not required. Some manufacturers have produced hybrid GPS equipment and offered retrofit GPS kits for installation in existing Transit/Omega receivers. This hybrid option has become significantly less attractive since the GPS constellation has reached full capability and Omega has begun phase-out.

Another hybrid variation is to combine a GPS receiver with a Loran-C receiver. When a GPS solution is available, the position information can be used to calibrate the Loran-C receiver for daily and local effects. When a GPS solution is not available, the calibrated Loran-C receiver can be used as a stand-alone system. When GPS satellites become visible again, the Loran-C can be used to initialize the GPS receiver and therefore reduce acquisition time. A combination of Loran-C and GPS data can also be used to produce a position solution or provide an automated cross-check for integrity purposes.

9.1 INTRODUCTION

A GPS receiver measures pseudoranges and pseudorange rates to the satellites. Knowing the position of the satellites from the decoded navigation messages, the user position and GPS system time can be calculated from four or more satellites.

A GPS receiver, however, can never measure exact range to each satellite. The measurement process is corrupted by noise which introduces errors into the calculation. This noise includes errors in the ionospheric corrections and system dynamics not considered during the measurement process (e.g., user clock drift). A Kalman filter characterizes the noise sources in order to minimize their effect on the desired receiver outputs.

When the GPS receiver is aided or integrated with other navigation sensors (e.g., INS, clock, altimeter or AHRS), then the Kalman filter can be extended to include the measurements added by these sensors. In fact, a typical implementation for integrated systems would be to have a central Kalman filter incorporating measurements from all available sources.

9.2 KALMAN FILTER PRINCIPLE

The Kalman filter is a linear, recursive estimator that produces the minimum variance estimate in a least squares sense under the assumption of white, Gaussian noise processes. Because the filter is a linear estimator by definition, for navigation systems it generally estimates errors in the total navigation state. The Kalman filter also produces a measure of the accuracy of its error state vector estimate. This level of accuracy is the matrix of second central moments of the errors in the estimate and is defined as the covariance matrix.

There are two basic processes that are modeled by a Kalman filter. The first process is a model describing how the error state vector changes in time. This model is the system dynamics model. The second model defines the relationship between the error state vector and any measurements processed by the filter and is the measurement model.

Intuitively, the Kalman filter sorts out information and weights the relative contributions of the measurements and of the dynamic behavior of the state vector. The measurements and state vector are weighted by their respective covariance matrices. If the measurements are inaccurate (large variances) when compared to the state vector estimate, then the filter will deweight the measurements. On the other hand, if the measurements are very accurate (small variances) when compared to the state estimate, then the filter will tend to weight the measurements heavily with the consequence that its previously computed state estimate will contribute little to the latest state estimate.

9.2.1 Kalman Filter Model

9.2.1.1 The System Dynamics Process

The system dynamics process is the model of how the error state vector transitions over time. The total navigation state is defined here to mean position, velocity, and perhaps attitude. The rate of change of the total navigation state will then be a nonlinear function of the state, and is assumed to be driven by white noise. Let $\underline{y}$(t) denote the total navigation state and $\hat{y}$(t) its estimate. The error in the estimated total navigation state is defined to be $\underline{x}$(t) $\underline{\underline{\Delta}}$ $\hat{y}$(t) - $\underline{y}$(t). The nonlinear differential equation representing the time rate of change of the estimated navigation state is expanded in a Taylor's series and differenced with the equation for the true state. By ignoring higher order terms, a linear differential equation for the time rate of change of the navigation error state is obtained.

It is natural to consider the behavior of the error state vector at discrete instants of time since a computer is used to implement the Kalman filter. Let $\underline{x}_k = \underline{x}(t_k)$ denote the error state vector at time t_k. Then the discrete form of the continuous error state differential equation is

$$\underline{x}_k \;=\; \Phi_{k-1}\;\underline{x}_{k-1} \;+\; G_{k-1}\;\underline{w}_{K-1}$$

The matrix F_{k-1} is the state transition matrix and describes how the error state vector changes with time. The sequence $\{\underline{w}_k\}$ is a white, zero mean Gaussian noise sequence called the process noise or plant noise. The expected value of the outer product of the vector $\underline{w}_k$ with itself is a matrix of the second central moments of the components of the noise vector. This covariance matrix has the variances of the components of $\underline{w}_k$ on the diagonal and the covariances of the components on the off diagonal, and is defined to be $E[\underline{w}_k\,\underline{w}_k^T] = Q_k$ where E[*] is the expectation operator.

9.2.1.2 The Measurement Process

The measurement model defines how the error state vector is related to measurements provided by sensor(s). Some examples of sensors are doppler velocimeter providing line-of-sight velocity, radar altimeter used to form terrain based measurements of position, such as for TERCOM, or GPS considered as a sensor giving position and velocity or raw pseudorange and deltarange measurements. Similar to the total navigation state differential equation, the measurement is often a nonlinear function of the total navigation state. By expanding the measurement equation for the estimated navigation state in terms of its error state and neglecting higher order terms, a linear measurement equation is obtained for the error state vector. The measurement equation is written in discrete form as

$$\underline{z}_k \;=\; H_k\;\underline{x}_k \;+\; \underline{v}_k$$

where $\underline{z}_k$ is the measurement at time t_k, H_k is the measurement matrix, (or sometimes called the measurement observation, or measurement sensitivity matrix), and $\{\underline{v}_k\}$ is a white, zero mean Gaussian sequence with covariance matrix $E[\underline{v}_k \underline{v}_k^T] = R_k$.

9.2.2 Kalman Filter Algorithm

The Kalman filter algorithm recursively estimates the error state vector. It also calculates the uncertainty in its estimate as given by its covariance matrix. Define $\hat{\underline{x}}_k$ to be the estimate of the error state vector at time t_k. The estimation error is the error in this estimate, or $\underline{dx} \triangleq \underline{x} - \hat{\underline{x}}$. The covariance matrix of the estimation error at time t_k gives a measure of the uncertainty in the estimated error state vector and is defined as

$$P_k = E[\underline{\ x}\,(\underline{\ x})^T] = E[(\underline{x}_k - \hat{\underline{x}}_k)\,(\underline{x}_k - \hat{\underline{x}}_k)^T]$$

The system dynamics model defines the behavior of the error state vector as a function of time. The measurement model defines the correspondence between the measurement and the error state. The measurements are assumed to be available at discrete times. The Kalman filter uses the dynamics model to propagate its estimated state vector between measurements. It then incorporates the measurement into the error state estimate. A Kalman filter repetitively performs propagations and updates of its estimated error state and its associated covariance matrix. Figure 9-1 is a simplified diagram of the Kalman filter as it processes new measurements and propagates in time.

9.2.2.1 Propagation

In the following equations, the notation '(-)' is appended to a variable to denote that variable at a measurement time before the measurement is incorporated. The symbol '(+)' appended to a variable represents that parameter at a measurement time immediately after the measurement is incorporated.

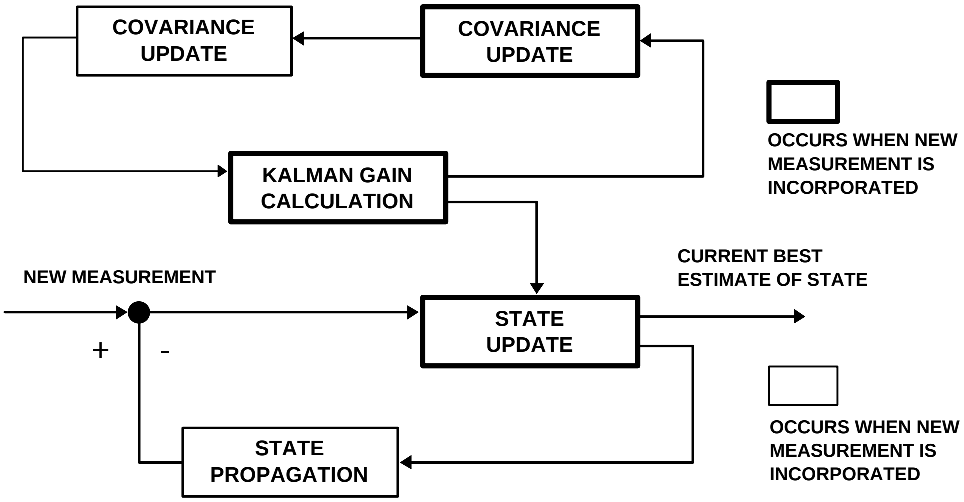


Figure 9-1. Simplified Diagram of Kalman Filter

The estimated error state vector and its covariance matrix are propagated from one measurement time to the next. The Kalman filter uses the state transition matrix and process noise covariance matrix to perform the propagations via

$$\underline{\hat{x}}_k(-) = \Phi_{k-1} \, \underline{\hat{x}}_{k-1}(+)$$

$$P_k(-) = \Phi_{k-1} \, P_{k-1}(+) \, \Phi_{k-1}^T + G_{k-1} \, Q_{k-1} \, G_{k-1}^T$$

Typically the impact of the propagation on the covariance matrix is to increase the variances of the non-bias estimated error states, although occasionally some of the variances may decrease, for example when due to the Schuler effect. The Schuler effect is a sinusoidal oscillation of inertial navigation errors with an 84 minute period.

9.2.2.2 Update

The Kalman filter incorporates measurements when they are available. Since the state carried in the Kalman filter is an error state, the measurement $\underline{z}_k$ is a function of the error state vector, and is usually referred to as the apriori measurement residual. The estimated error state vector is updated as

$$\underline{\hat{x}}_k(+) = \underline{\hat{x}}_k(-) + K_k \, (\underline{z}_k - H_k \, \underline{\hat{x}}_k(-))$$

The quantity $\underline{z}_k$ - H_k $\underline{\hat{x}}_k(-)$ is the aposteriori residual, or equivalently the kth element of the innovations sequence, the sequence of new information from the measurements. The matrix K_k is the Kalman gain and is given by

$$K_K = P_k(-) \, H_k^T \, (H_k \, P_k(-) \, H_k^T + R_k)^{-1}$$

The updated covariance matrix can be derived directly from the equation for the updated state, yielding the symmetric Joseph form

$$P_k(+) = (I - K_k \, H_k) \, P_k(-) \, (I - K_k \, H_k)^T + K_k \, R_k \, K_k^T$$

Using the definition of the Kalman gain, the equation for the updated covariance matrix can be reduced to

$$P_k(+) = (I - K_k H_k) P_k(-)$$

Although much simpler than the Joseph form, caution must be exercised if this equation is used since it is susceptible to numerical problems. Since P is a covariance matrix, theoretically it is symmetric and nonnegative definite (all eigenvalues ³ 0). One approach to insure that P is always nonnegative definite is to factor the initial P as a product of upper (or lower) unit triangular matrices and a diagonal matrix as

$$P = U D U^T$$

Here U is unit triangular and D is diagonal. If the initial P is nonnegative definite, then all elements of D will be ³ 0. Algorithms exist to propagate and update the factors U and D instead of P so that P need never explicitly be formed. These algorithms operate on U and D in a manner that guarantees that the elements of D are always ³ 0, implying that P is always nonnegative definite. Other algorithms can also be used to ensure the positive definiteness of P. The matrix P can be factored into a product of lower triangular and diagonal matrices, exactly equivalent to the UD factorization, or P may be factored into its square root as $P = W W^T$ (square root formulation).

Although the equation for the Kalman gain seems complex, a simple example will help develop an intuitive feel for this gain calculation. Note first that the updated state estimate can be rewritten as

$$\underline{\hat{x}}_k(+) = (I - K_k H_k) \underline{\hat{x}}_k(-) + K_k \underline{z}_k$$

Assume that the state and measurement are scalars and that the measurement matrix H is 1. Then the Kalman gain is

$$K = P / (P + R)$$

For large uncertainty in the state model (P » R), as P ® ¥, then K ® 1. As K ® 1, then $\underline{\hat{x}}_k(+)$ ® $\underline{z}_k$. In other words, given the large uncertainty in the state, the new measurement is assumed to be a much better estimate of the state than is the propagated estimate. On the contrary, for large uncertainty in the measurement compared with the estimated state, R » P, then as R ® ¥, K ® 0. As K ® 0, then $\underline{\hat{x}}_k(+)$ ® $\underline{\hat{x}}_k(-)$. Thus the new information is essentially ignored since the apriori estimate is deemed much better than the measurement. This is an inherent danger in Kalman filters; once K becomes sufficiently close to zero, the filter will respond very slowly or not at all to new information. Most Kalman filters incorporate an artificial lower limit on K to prevent this from happening.

9.2.2.3 Initial Conditions

The Kalman filter state estimate and covariance matrix need to be established at the initial time. Then the propagations and updates proceed as noted. The initial state estimate $\underline{\hat{x}}_0$ is set to the expected value of the state at t_0. Without any prior knowledge, the initial error state estimate is often set to the zero vector. The initial covariance matrix P_0 reflects the uncertainty associated with the way in which the total navigation state is initialized.

9.3 KALMAN FILTERING FOR UNAIDED GPS

9.3.1 The GPS Navigation Process

GPS signals are timed at their arrival at the receiver by the code loop correlation process. The total slew of the bit edge that achieves maximum correlation with the incoming code is the time offset from the local reference time. The time of broadcast is contained in the navigation message, which is decoded in the receiver after correlation. The difference between the time of broadcast and the time of arrival is the transit time from the satellite to the receiver. This includes the receiver and satellite clock offsets from the GPS time.

Multiplication of the calculated time of transit by the speed of transmission (light) results in a measurement of pseudorange. Corrections may be made to this pseudorange for the assumed, modeled, or measured tropospheric and/or ionospheric delays. In stand-alone operation of single frequency receivers, the modeled corrections are generally applied. Dual frequency receivers will measure the ionospheric delay directly and apply a smoothed value.

The measurement process is corrupted by noise which introduces errors into the calculations. Examples of errors are receiver clock drift, errors in the ionospheric corrections and system dynamics not considered during the measurement process.

With four pseudorange measurements to four different satellites, the absolute position and user clock offset could be found. Algorithms exist to analytically find the user position and clock offset from a set of four pseudorange measurements. A solution is usually implemented with an assumed rough location and iterative updates to that location, essentially an application of Newton's root finding method as implemented in a Kalman filter.

The velocity of the GPS receiver is computed by processing the relative velocity along the line-of-sight between the satellite and the receiver. This relative velocity is usually obtained by measuring the Doppler offset of the incoming carrier signal. The measurement is called deltarange which includes the receiver clock frequency drift. Similar to the position computation, the receiver clock error (drift in the case of deltarange measurements) is an unknown parameter and should be resolved along with the absolute velocity.

Deltarange measurements can be computed by summing up the carrier voltage-controlled oscillator (VCO) commands in the carrier tracking loop which tracks the phase of the received signal. The changes in measured phases are fed back to the VCO to zero out these changes.

As with the pseudorange measurements, four deltarange measurements to four different satellites allow velocity and user clock drift to be computed analytically, although an iterative procedure is typically employed.

9.3.2 The GPS Navigation Equation

Figure 9-2 shows the basic relation between the line-of-sight pseudorange measurement PR_i (i=1,..,4 satellites), the satellites positions (S_{xi}, S_{yi}, S_{zi}), and the (antenna) user position coordinates (U_x, U_y, U_z). The equation for the pseudorange is as follows:

$$PR_i = [(S_{xi} - U_x)^2 + (S_{yi} - U_y)^2 + (S_{zi} - U_z)^2]^{1/2} + b_u$$

where

PR_i = pseudorange to the ith satellite, measured in the code correlation process

S_{xi}, S_{yi}, S_{zi} = position coordinates of the ith satellite, known from the decoded navigation message

U_x, U_y, U_z = three coordinates of the user position, to be found

b_u = contribution to pseudorange caused by the user clock offset error, to be found

The equations for deltarange are similar:

$$dPR_i = [(V_{xi} - V_x)^2 + (V_{yi} - V_y)^2 + (V_{zi} - V_z)^2]^{1/2} + f_u$$

where

dPR_i = deltarange to the ith satellite, measured in the phase lock loop

V_{xi}, V_{yi}, V_{zi} = velocity coordinates of the ith satellite, derived from the decoded navigation message

V_x, V_y, V_z = three coordinates of the user velocity, to be found

f_u = contribution to deltarange caused by the frequency bias, to be found

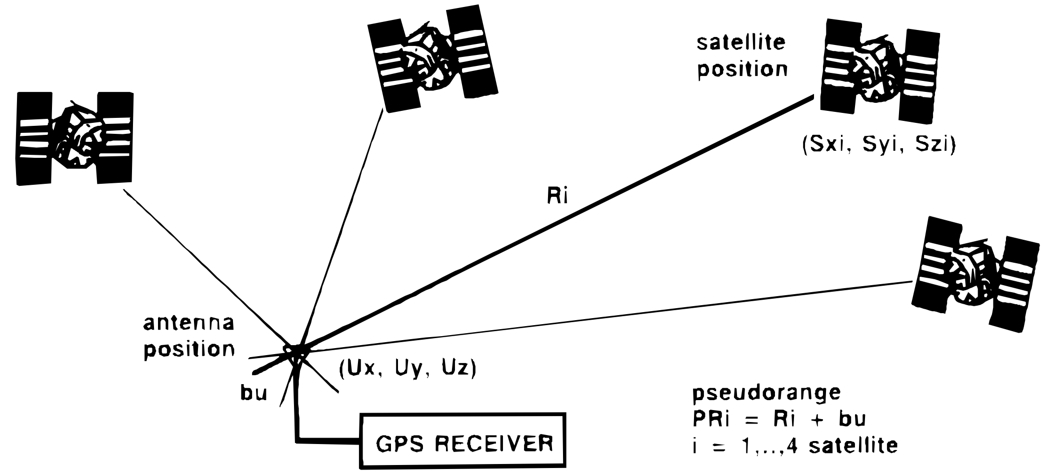


Figure 9-2. Geometry for GPS Measurement

Note that since the deltarange measurements are found by a scaled sum of VCO commands from the carrier tracking loops, the average receiver and satellite velocities over the deltarange dwell time should be used in the above equations instead of instantaneous velocities. The average velocity can be approximated by the velocity at the midpoint of the deltarange interval.

With four pseudorange measurements, there are four simultaneous quadratic equations with four unknowns, the three coordinates of user position and the user's receiver clock offset. Except in unusual geometric conditions, there exists a solution. In practice, there are many computations to be made before arriving at this equation. For example, the satellite positions are broadcast as orbital parameters (ephemerides) and are a function of current time. In all, 24 variables must be computed or solved from the available information.

9.3.3 The GPS Kalman Filter Model

To cast the Kalman filter equations in GPS form for the unaided receiver, the state vector must be defined and the system dynamics and measurement matrices must be formulated. As a minimum, typically an eight state error vector is chosen: position error (dx, dy, dz), receiver clock phase error (b_u), velocity error (dv_x, dv_y, dv_z) and receiver clock frequency error (f_u):

$$\underline{x} = (x, y, z, b_u, v_x, v_y, v_z, f_u)^T$$

The state transition matrix for the dynamic model can take various forms. Often, unaided receivers will model the vehicle motion as a constant velocity with process noise to account for accelerations. In that case the propagation equations are as follows:

$$d(x, y, z)/dt = (v_x, v_y, v_z)$$

$$d(b_u)/dt = f_u$$

$$d(v_x, v_y, v_z)/dt = (0, 0, 0)$$

$$d(f_u)/dt = 0$$

For a small propagation time interval of Dt the F matrix would be:

$$\Phi = \begin{vmatrix} I & I\Delta t \\ O & I \end{vmatrix}$$

where I is the 4 x 4 identity matrix. The measurement vector for each (i th) satellite measurement contains the pseudorange PR_i and pseudorange rate dPR_i (= dPR_i/dt):

$$\underline{z}_y = (PR_i, dPR_i)^T$$

Define

range vector $\underline{R}_i$ = $(S_{xi}-U_x, S_{yi}-U_y, S_{zi}-U_z)$
range R_i = $|\underline{R}_i|$
PR_i measurement = $(S_{xi}-U_x, S_{yi}-U_y, S_{zi}-U_z)\cdot\underline{R}_i/R_i + b_u$
dPR_i measurement = $(V_{xi}-V_x, V_{yi}-V_y, V_{zi}-V_z)\cdot\underline{R}_i/R_i + f_u$

and where (S_{xi}, S_{yi}, S_{zi}) and (V_{xi}, V_{yi}, V_{zi}) are the components of the computed satellite position and velocity respectively. The matrix H has two different types of rows, one type for pseudorange

$$[-(S_{xi} - U_x)/R_i,\ -(S_{yi} - U_y)/R_i,\ -(S_{zi} - U_z)/R_i,\ 1,\ 0,\ 0,\ 0,\ 0]$$

and a similar row for pseudorange rate

$$[0,\ 0,\ 0,\ 0,\ -(S_{xi} - U_x)/R_i,\ -(S_{yi} - U_y)/R_i,\ -(S_{zi} - U_z)/R_i,\ 1]$$

9.3.4 GPS Augmented Kalman Filter

A modification of this formulation is to include three acceleration states in addition to the position and velocity states. Although there is no direct measurement of acceleration in the unaided GPS receiver, these augmented states aid the filter in sorting out non-zero mean errors. Specifically, if these states are included, and the vehicle undergoes constant acceleration, the apparent discrepancy in the velocity data will build up as a bias in the acceleration states, and the resultant filter accuracy will improve. In essence, these states represent an unknown bias error in the states related to the velocity terms by their first difference, so the filter assumes that any such errors belong in these states. Of course, if the acceleration is not constant, the acceleration states will not perfectly track the error, and in fact the filter will respond more sluggishly to the velocity changes. But for the case of an aircraft with constant acceleration turns, the augmented state filter will outperform the eight-state filter.

9.3.5 GPS Kalman Filter Tuning

It is important to note that the covariance matrix is actually an estimate of the statistics of the estimation error vector. Mismodeling of the system dynamics or of the process or measurement noises can cause the true estimation error uncertainties to be quite different from the covariance matrix computed by the Kalman filter. Modeling only a subset of the total set of errors (suboptimal Kalman filter) will also cause an inaccurate covariance matrix. When this occurs, the accuracy of the navigation system may be substantially degraded. The process whereby the covariance matrix of the mechanized filter is made to closely approximate the true covariance matrix is referred to as Kalman filter tuning.

One way in which GPS Kalman filters are often tuned is through the use of adaptive tuning. Specifically, this refers to dynamically setting the process noise Q as a function of vehicle motion. This approach is used to account for mismodeling in the state dynamics model. In this case, the errors are not Gaussian noise, but may be biases in turns as already shown. Therefore, the correct Q depends on the vehicle profile. For straight and level flight, a small Q is appropriate. For turns or higher dynamics, Q must be larger. For filter stability reasons, Q must be set to the highest level of uncertainty expected. This means that in straight and level flight, for example, the Q will be overly pessimistic and will force processing too much noise from the measurements due to larger Kalman gains than needed.

The answer is to adapt Q, by setting it as small as possible, then using some other observation to boost Q when needed. Some schemes tried in GPS receivers include making Q a function of the ratio of the observed measurement residuals with the assumed measurement noise. The only danger here is that if Q is allowed to adapt too quickly, the filter can get into a positive feedback loop and cause instability. This happens when observed noise opens Q which creates more noise, etc. The resolution of this problem is to make Q adaptation very slow so that only longer trend conditions cause a change in Q. In practice, the adaptation may be implemented directly on the covariance rather than the Q term, but the effect is similar.

9.4 KALMAN FILTERING FOR AIDED/INTEGRATED GPS

9.4.1 The Integrated Navigation Solution

GPS provides accurate position, velocity and time and is designed to perform in all-weather, at any time of the day, and under specified conditions of jamming and HV dynamics. Despite its superb performance, many integrators choose to go one step further and combine GPS with other navigation sensors and systems available in the HV into an integrated navigation solution. Similar to the basic GPS navigation equations, this integrated solution is using a Kalman filter to combine the individual navigation solutions.

Since GPS is the most accurate positioning system with worldwide coverage currently available, the integrated system navigation solution will essentially be based on the GPS solution when GPS is available. The system design will be driven by the unifying concern for continued high quality navigation when the GPS solution is unavailable because of jamming, dynamics or satellite failures.

Technical considerations for integrations of GPS with other sensors include the choice of system architecture, the hosting of the Kalman filter, and the characterization and modeling of additional measurements added by the other sensors. The most important integration is the one in which GPS is combined with an INS. Besides the combination of GPS and INS, the integration can also benefit from sensors in the HV such as a precise clock, barometric altimeter or an AHRS in the absence of an INS.

9.4.2 Kalman Filtering and GPS/INS

9.4.2.1 System Architecture

There are basically four different architectures possible in the combined GPS/INS implementation, depending on the choice of hosting the Kalman filter and the choice of open or closed-loop technique. Whether the integrated filter uses position and velocity derived from the GPS Kalman filter or uses pseudoranges and deltaranges is usually referred as loosely coupled or tightly coupled respectively.

The simplest way to combine GPS and INS is a reset-only mechanization in which GPS is used to periodically reset the INS solution (see Figure 9-3). In this loosely coupled, open-loop strategy the INS is not recalibrated by GPS data, so the underlying error sources in the INS still drive its navigation errors as soon as GPS resets are interrupted. However, for short GPS interruptions or for high quality INS, the error growth may be small enough to meet mission requirements.

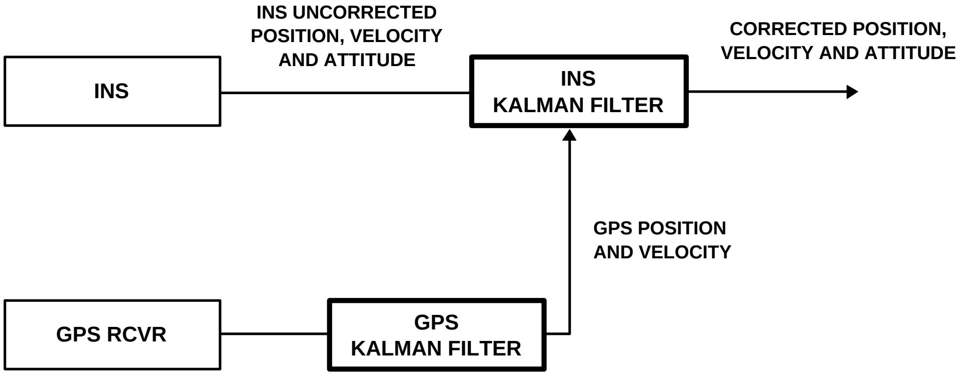


Figure 9-3. Open-loop GPS/INS Aided Architecture

The main advantage of GPS aiding the INS in a closed-loop mechanization is that the inertial system is continuously calibrated by the Kalman filter, using the GPS observables (see Figure 9-4). When GPS is lost due to jamming, dynamics or satellite shadowing, the inertial system can continue to derive its navigation solution, but now with a greater degree of precision by virtue of its recent calibration. However, this loosely coupled, closed loop technique has serious potential stability problems in cases where the INS feeds back navigation data to the GPS receiver.

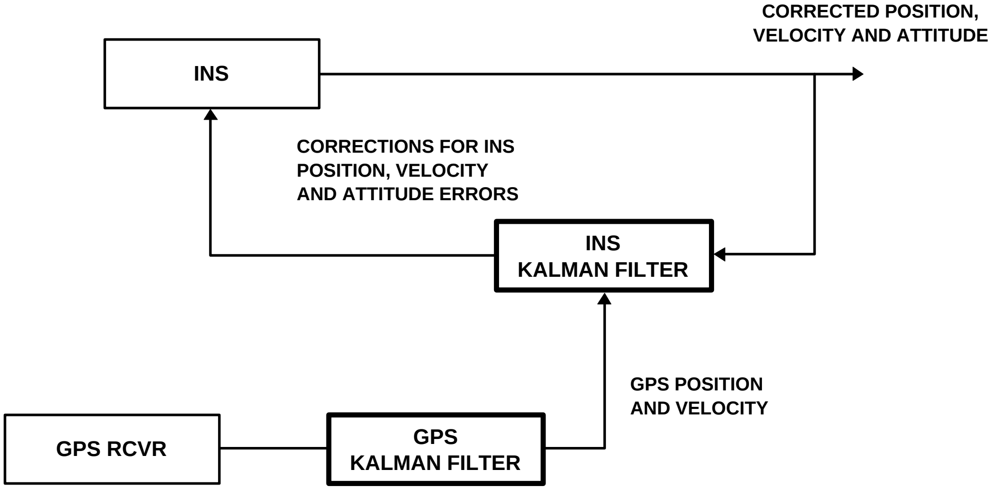


Figure 9-4. Closed-Loop GPS/INS Aided Architecture

GPS aiding the INS (loosely coupled) in both open and closed-loop modes results in the simplest implementation: any GPS receiver and any INS with the necessary data interfaces can be used and it requires a smaller Kalman mechanization of the integrated INS filter since the INS treats the GPS receiver merely as another sensor. Disadvantages are the use of two separate Kalman filters with the potential instability of cascaded filters, and that the GPS Kalman filter provides correlated position and velocity measurements that may not be modeled adequately in the INS filter.

The next level of integration is the tightly coupled, open-loop integrated GPS/INS Kalman filter which requires implementation at pseudorange level (see Figure 9-5). This approach has more complex measurement equations but requires only one Kalman filter mechanization. The filter can be closer to optimal since effects of satellite geometry and INS errors are included and INS aiding throughout a GPS outage can be provided. Only one navigation solution is computed and both carrier and code tracking loop aiding can be done using the velocity and attitude data from the INS.

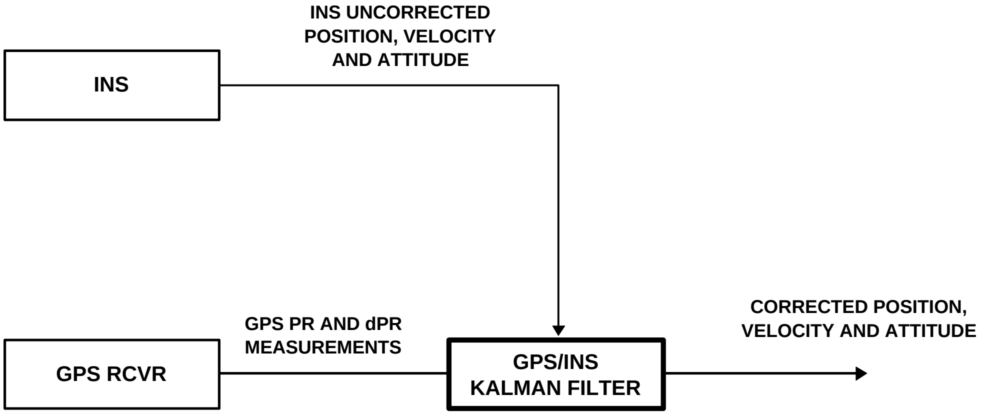


Figure 9-5. Open-loop Integrated GPS/INS Architecture

The highest level of integration is the tightly coupled, closed-loop integrated GPS/INS Kalman filter (see Figure 9-6). In addition to having only one Kalman filter and the other benefits of the tightly coupled, open-loop filter, the main advantage here is that the INS is continuously calibrated and will maintain the most accurate navigation solution in case of GPS outages.

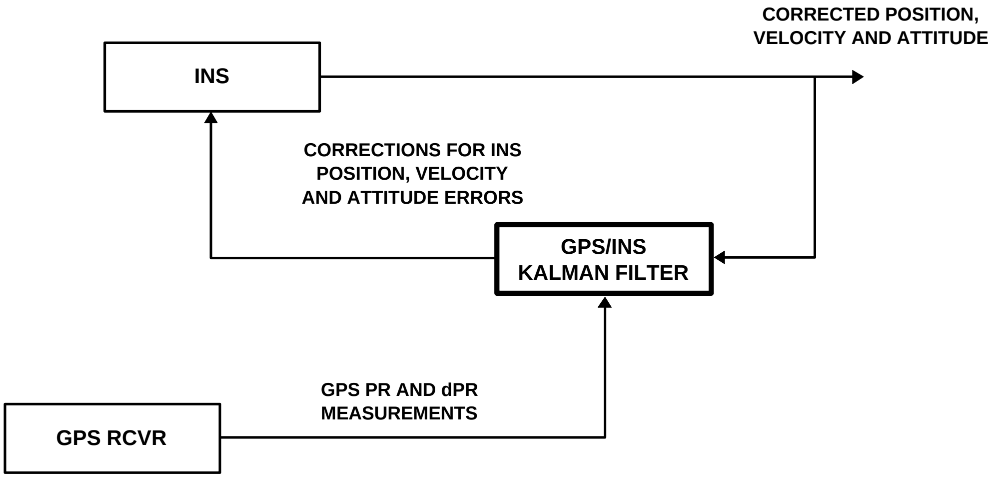


Figure 9-6. Closed-loop Integrated GPS/INS Architecture

9.4.2.2 The INS Navigation Process

The INS Kalman filter will model and estimate some of the INS errors. An INS consists of, as a minimum, an Inertial Measurement Unit (IMU) and a computer to perform processing. The inertial sensors are accelerometers and gyroscopes which measure, loosely speaking, inertial accelerations and rotations.

Most IMU's fall into one of two classes. The first, and oldest type, is a gimballed platform. In a gimballed IMU, the accelerometer triad is mounted on a platform that is maintained stable in inertial space by the gyros. A locally level navigation frame is usually mechanized so that the gyros are "torqued" for transport and earth rates to force the platform to remain perpendicular to the local gravity vector. Thus the accelerometers measure accelerations directly in the local level plane. Many gimballed platforms also include a third accelerometer orthogonal to the two in the platform plane that measures vertical specific force. The attitude of the IMU case with respect to the platform is determined through electrical pickoffs of the gimbal structure.

The second type of IMU is the strapdown system. In a strapdown IMU, the gyros are rate integrating and are essentially hard mounted to the host vehicle. The gyros measure incremental angular change. The computer must keep track of the angular changes so that the attitude of the host vehicle can be determined. The three accelerometers measure linear accelerations as in the case of a gimballed IMU, although the accelerations are in the vehicle body frame. The transformation from the platform to navigation frames is used to convert the accelerations to navigation coordinates where they are integrated to produce velocity and position.

To summarize, an INS consists of three major subsystems:

1. Attitude subsystem where the orientation of the IMU with respect to the navigation frame is maintained

2. Specific force sensing subsystem, usually three single-axis accelerometers, that measure accelerations

3. Computation subsystem, in which INS navigation equations of motion are solved.

Depending upon the instrument quality, INS position error rates can range from 0.1 nm/hr to 10.0 nm/hr. Although the INS errors can grow unbounded, their temporal behavior has a very well defined frequency behavior. Horizontal errors will oscillate at the Schuler frequency (with an 84-minute period) modulated by earth rate (24 hour period) and the second order Foucault frequency (period depends on vehicle velocity, direction, and latitude).

The pure inertial vertical channel of an INS is unstable with a time constant of 9.5 minutes. For this reason many inertial navigation systems incorporate baro -altimeter stabilization of its vertical channel. Note that for GPS/INS integrated filters, the baro-altimeter error can be estimated through GPS position measurements. Since direct GPS measurements of position yield reference ellipsoid altitude, the baro-altimeter error estimated includes the offset of local mean sea level from the ellipsoid.

An important error source in an INS is an error in knowledge of the orientation or alignment of the INS sensor package with respect to its navigation frame. These misalignment errors are usually expressed as three small rotation angles and are referred to as platform tilts. In a strapdown INS, the three angles are related to pitch, roll and heading error, while in a gimballed system the angles are identified with rotations of the platform about the level and vertical axes.

The three accelerometers in an INS are usually mounted in a mutually orthogonal triad, each one measuring a component of specific force along its sensitive axis. Typical accelerometer errors include bias, scale factor, and misalignments among others. A bias error means that the instrument reading is always off by a fixed amount of acceleration. A scale factor error refers to an error in the accelerometer output by a constant multiplicative factor. An accelerometer misalignment will cause the accelerometer to sense components of accelerations that occur along an axis supposedly orthogonal to its input axis.

An INS usually has gyros mounted with their sensitive axes in a mutually orthogonal triad. The gyros may be single or dual axis (2 degree-of-freedom) in nature. Two 2 degree-of-freedom gyros provide outputs along 3 orthogonal axes and along 1 redundant axis. The gyro axes have a known, fixed orientation with respect to the accelerometers. A gyro drift rate or bias is a constant angular rate of change of the platform tilts. Gyros errors also include scale factor errors, misalignments, and in the case of spinning mass gyros, g-sensitive drift rates. The gyro bias errors are the primary cause of increasing horizontal position errors and consequently are the errors most necessary to minimize for longer missions.

9.4.2.3 The INS Kalman Filter States

For an INS Kalman filter implementation, 15 states are often used to describe the INS navigation process and its error sources:

- 3 INS position errors
- 3 INS velocity errors
- 3 platform orientation errors
- 3 accelerometer biases
- 3 gyro drift rates

For some applications, particularly if the mission scenario calls for only short periods of time without GPS data, it may be possible to model an INS with fewer states.

There are many other sources of error in an INS in addition to the states given above as noted previously: gyro and accelerometer scale factor errors, gyro and accelerometer input axis misalignment angles, gyro g-sensitivity, etc. Usually the effects of these errors are accounted for in the computation of the process noise covariance matrix Q. Failure to account for the effects of these errors will almost always result in optimistic filter performance; that is, the true estimation error standard deviations will be larger than the standard deviations in the covariance matrix computed by the Kalman filter. In addition, the INS manufacturer attempts to minimize their effects by providing calibration coefficients and test data on the INS themselves.

9.4.3 Kalman Filtering and GPS/Precise Clock

In case an external clock is used for GPS time reference, its phase and frequency error can be included as states in the Kalman filter. Corrections are calculated and either maintained in the mission computer (open-loop) or directly applied to the clock continuously (closed-loop).

When the receiver starts to navigate with only three satellites, the calibrated clock can then be used to maintain accurate GPS system time. This also applies to a two satellite situation if receiver altitude is known. What accuracy can be maintained and for how long depends on the detail of the error models and the disturbance to the clock during the outage period. Examples of such disturbances are temperature changes, pressure changes, crystal aging, accelerations and vibrations.

9.4.4 Kalman Filtering and GPS/Barometric Altimeter

A barometric altimeter is typically included in a stand-alone INS for damping of its otherwise unstable vertical loop. In a GPS/INS integration, inclusion of a barometric altimeter is recommended both for aiding poor vertical geometry situations under nominal conditions and for three-satellite situations. If GPS outages occur for extended periods of time, then some other type of reference altitude is required to stabilize the vertical channel.

The barometric altimeter can be processed as a measurement to the Kalman filter since the vertical channel is effectively stabilized through the optimal Kalman filter gains. In this case, the barometric altimeter error is modeled in the Kalman filter state vector. The barometric altimeter measurement will only be processed by the Kalman filter when GPS satellite coverage is incomplete. If not processed as a measurement to the Kalman filter, the barometric altitude can be differenced with inertial altitude to create an error signal that is filtered and fed back to inertial altitude, giving a blended baro/inertial altitude.

9.4.5 Kalman Filtering and GPS/AHRS

An AHRS is a strapdown system which uses lower quality gyros and accelerometers than a strapdown INS. Used as a stand-alone system, an AHRS is similar to an INS, except that no position is available, only attitude (pitch, roll and heading), attitude rates and acceleration.

GPS can provide three-dimensional bounded position and velocity aiding information to the AHRS to improve its outputs. An AHRS, in its turn, can be used for short-term fill-in of velocity information if the receiver outputs are lost. Potentially, AHRS velocity could also aid the GPS receiver tracking loops during short periods of jamming or high dynamics. The separate Kalman filter, in case of an aided GPS/AHRS, does not include the vertical channel. A typical Kalman filter model has 14 error states: horizontal position (2), horizontal velocity (2), rotations (2), gyro drift rates (3), gyro scale factor (1), wander-azimuth angle (1) and accelerometer bias (3). The combined Kalman filter for a tightly coupled, integrated GPS/AHRS adds four error states: vertical position, vertical velocity, clock phase error and clock frequency error.

10.1 INTRODUCTION

Differential GPS (DGPS) was developed to meet the needs of positioning and distance measuring applications that required higher accuracies than stand-alone GPS could deliver. A typical differential GPS architecture (see Figure 10-1) consists of a reference receiver located at a surveyed, known location, and one or more DGPS user receivers. The user receivers are often called "mobile" receivers because they are not confined to a fixed location like the reference receiver. The Reference Receiver antenna, differential correction processing system, and data link equipment (if used) are collectively called the Reference Station. Both sets of receivers either collect and store the necessary data for later processing, or send them to the desired location in real time via the data link.

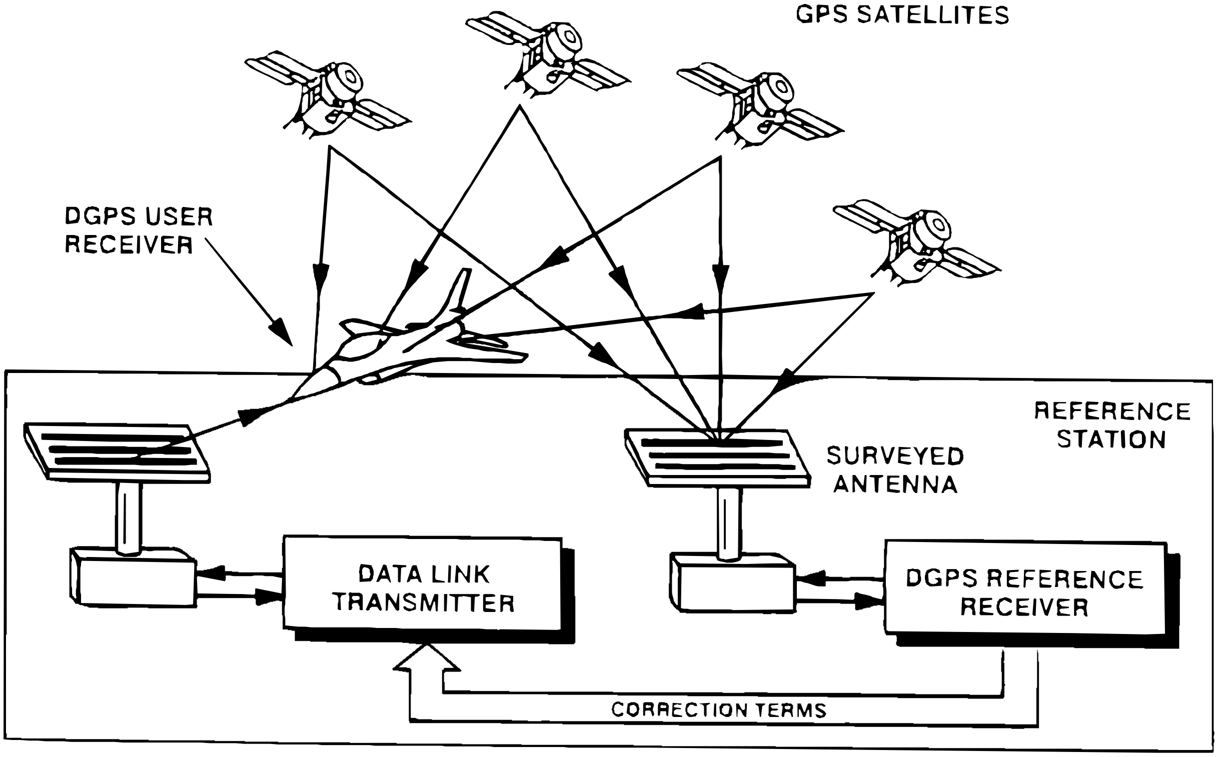


Figure 10-1. Typical Differential System Architecture

This overview outlines some of the fundamental issues of DGPS. These issues should be considered by any user considering the need for a positioning system that can give accuracies better than the absolute PPS or SPS performance.

10.2 DGPS CONCEPT

DGPS is based on the principle that receivers in the same vicinity will simultaneously experience common errors on a particular satellite ranging signal. In general, the user (mobile) receivers use measurements from the reference receiver to remove the common errors. In order to accomplish this, the user (mobile) receivers must simultaneously use a subset or the same set of satellites as the reference station. The DGPS positioning equations are formulated so that the common errors cancel. The common errors include signal path delays through the atmosphere, and satellite clock and ephemeris errors. For PPS users, the common satellite errors are residual system errors that are normally present in the PVT solution. For SPS users, the common satellite errors also include the intentionally added errors from SA. Errors that are unique to each receiver, such as receiver measurement noise and multipath, cannot be removed without additional recursive processing (by the reference receiver, user receiver, or both) to provide an averaged, smoothed, or filtered solution.

Various DGPS techniques are employed depending on the accuracy desired, where the data processing is to be performed, and whether real-time results are required. If real-time results are required then a data link is also required. For applications without a real-time requirement, the data can be collected and processed later. The accuracy requirements usually dictate which measurements are used and what algorithms are employed. Under normal conditions, DGPS accuracy is independent of whether SPS or PPS is being used, although real-time PPS DGPS can have a lower data rate than SPS DGPS because the rate of change of the nominal system errors is slower than the rate of change of SA. However, the user and the Reference Station must be using the same service (either PPS or SPS).

The clock and frequency biases for a particular satellite will appear the same to all users since these parameters are unaffected by signal propagation or distance from the satellite. The pseudorange and deltarange (Doppler) measurements will be different for different users, because they will be at different locations and have different relative velocities with respect to the satellite, but the satellite clock and frequency bias will be common error components of those measurements. The signal propagation delay is truly a common error for receivers in the same location, but as the distance between receivers increases, this error gradually decorrelates and becomes independent. The satellite ephemeris has errors in all three dimensions. Therefore, part of the error will appear as a common range error and part will remain a residual ephemeris error. The residual portion is normally small and its impact remains small for similar observation angles to the satellite.

The accepted standard for SPS DGPS was developed by the Radio Technical Commission for Maritime Services (RTCM) Special Committee-104 (SC-104). The RTCM developed standards for the use of differential corrections, and defined the data format to be used between the reference station and the user. The standards are primarily intended for real time operational use and cover a wide range of DGPS measurement types. Most SPS DGPS receivers are compatible with the RTCM SC-104 differential message formats. DGPS standards have also been developed by the Radio Technical Commission for Aeronautics (RTCA) for special Category I precision approach using ranging-code differential. The standards are contained in RTCA document DO-217. This document is intended only for limited use until an international standard can be developed for precision approach.

10.3 DGPS IMPLEMENTATION TYPES

There are two primary variations of the differential measurements and equations. One is based on ranging-code measurements and the other based on carrier-phase measurements. There are also several ways to implement the data link function. DGPS systems can be designed to serve a limited area from a single reference station, or can use a network of reference stations and special algorithms to extend the validity of the DGPS technique over a wide area. The result is that there is a large variety of possible DGPS system implementations using combinations of these design features.

10.3.1 Ranging-Code Differential

The ranging-code differential technique uses the pseudorange measurements of the reference station to calculate pseudorange or position corrections for the user receivers. The reference station calculates pseudorange corrections for each visible satellite by subtracting the "true" range, determined by the surveyed position and the known orbit parameters, from the measured pseudorange. The user receiver then selects the appropriate correction for each satellite that it is tracking, and subtracts the correction from the pseudorange that it has measured. The mobile receiver must only use those satellites for which corrections have been received.

If the reference station provides position corrections rather than pseudorange corrections, the corrections are simply determined by subtracting the measured position from the surveyed position. The advantage of using position corrections is obviously the simplicity of the calculations. The disadvantage is that the reference receiver and the user receiver must use the exact same set of satellites. This can be accomplished by coordinating the choice of satellites between the reference receiver and the user receiver, or by having the reference station compute a position correction for each possible combination of satellites. For these reasons, it is usually more flexible and efficient to provide pseudorange corrections rather than position corrections. The RTCM SC-104 and RTCA DO-217 formats are all based on pseudorange rather than position corrections.

The pseudorange or position corrections are time tagged with the time that the measurements were taken. In real-time systems, the rate of change of the corrections is also calculated. This allows the user to propagate the corrections to the time that they are actually applied to the user position solution. This reduces the impact of data latency on the accuracy of the system but does not eliminate it entirely. SPS corrections become fully uncorrelated with the user measurements after about 2 minutes. Corrections used after two minutes may produce solutions which are less accurate than stand-alone SPS GPS. PPS corrections can remain correlated with the user measurements for 10 minutes or more under benign (slowly changing) ionospheric conditions.

10.3.2 Carrier-Phase Differential

The carrier-phase measurement technique uses the difference between the carrier phases measured at the reference receiver and user receiver. A double-differencing technique is used to remove the satellite and receiver clock errors. The first difference is the difference between the phase measurements at the user receiver and the reference receiver for a single satellite. This eliminates the satellite clock error which is common to both measurements. This process is then repeated for a second satellite. A second difference is then formed by subtracting the first difference for the first satellite from the first difference for the second satellite. This eliminates both receiver clock errors which are common to the first difference equations. This process is repeated for two other pairs of satellites resulting in three double-differenced measurements that can be solved for the difference between the reference station and user receiver locations. This is inherently a relative positioning technique, therefore the user receiver must know the reference station location to determine its absolute position. Refer to Chapter 11 for a more detailed description of this process.

This same technique can be used to determine the attitude of a vehicle or platform. In this case the processing can be contained within one receiver using multiple fixed antennas. One antenna can be arbitrarily chosen as the "reference". Since the antennas are separated by fixed distances and since their relationship to the center-of-mass of the platform is known, it is possible to convert the carrier phase differences into angular differences between the antenna locations and the line-of-sight to a satellite. By using measurements from multiple satellites, or the position of the platform from a DGPS position fix, these angular differences can be transformed to represent the attitude of the platform with respect to the local vertical axis.

The "raw" phase measurements are essentially a count of the number of carrier cycles between the satellite and receiver positions. The number of cycles times the carrier wavelength is a range measurement. The receivers can directly measure the fractional portion of the phase measurement and can track phase shifts including whole cycles, but they must calculate the initial whole number of cycles between the receiver and the satellite. This is referred to as the integer cycle ambiguity.

For surveying applications, this integer ambiguity can be resolved by starting with the mobile receiver antenna within a wavelength of the reference receiver antenna. Both receivers start with the same integer ambiguity, so the difference is zero and drops out of the double-difference equations. Thereafter, the phase shift that the mobile receiver observes (whole cycles) is the integer phase difference between the two receivers. For other applications where it is not practical to bring the reference and mobile antennas together, the reference and mobile receivers can solve for the ambiguities independently as part of an initialization process. One way is to place the mobile receiver at a surveyed location. In this case the initial difference is not necessarily zero but it is an easily calculated value.

For some applications (such as aircraft precision approach), it is essential to be able to solve for the integer ambiguity at an unknown location or while in motion (or both). In this case, solving for the integer ambiguity usually consists of eliminating incorrect solutions until the correct solution is found. A good initial estimate of position (such as from ranging-code differential) helps to keep the initial number of candidate solutions small. Redundant measurements over time and/or from extra satellite signals are used to isolate the correct solution. These "search" techniques can take as little as a few seconds or up to several minutes to perform and can require significant computer processing power. This version of the carrier-phase DGPS technique is typically called kinematic differential GPS.

If carrier track or phase lock on a satellite is interrupted and the integer count is lost, then the initialization process must be repeated for that satellite (known as cycle clip). Output data flow may also be interrupted if the receiver is not collecting redundant measurements from extra satellites to maintain the position solution. If a precise position solution is maintained, reinitialization for the "lost" satellite can be almost immediate. Developing a robust and rapid method of initialization and reinitialization is the primary challenge facing designers of real-time systems that have a safety critical application such as aircraft precision approach.

10.3.3 DGPS Data Link Implementations

DGPS can also be implemented in several different ways depending on the type of data link used. The simplest data link is no data link at all. For non-real-time applications, the measurements can be stored in the receiver or on suitable media and processed at a later time. In most cases to achieve surveying accuracies, the data must be post-processed using precise ephemeris data that is only available after the survey data has been collected. Similarly, for some test applications the cost and effort to maintain a real-time data link may be unnecessary. Nevertheless, low-precision real-time outputs can be useful to confirm that a survey or test is progressing properly even if the accuracy of the results will be enhanced later.

Differential corrections or measurements can be uplinked in real-time from the reference station to the users. This is the most common technique where a large number of users must be served in real-time. If the user receivers are passive as in GPS itself, an unlimited number of users can be served. For military purposes and proprietary commercial services, the uplink can be encrypted to restrict the use of the DGPS signals to a select group of users.

An uplink can be a separate transmitter/receiver system or the DGPS signals can be superimposed on a GPS-like D-band ranging signal. The uplink acts as a pseudo-satellite or "pseudolite" and delivers the ranging signal and DGPS data via the RF section of the user receiver, much in the same way the GPS navigation message is transmitted. The advantages are that the additional ranging signal(s) can increase the availability of the position solution, or decrease carrier-phase initialization time, and a separate data link system is not required. However, the reference station and user receivers become more complex and the pseudolite can become a GPS jammer if it overpowers the GPS satellite signals.

A downlink option is also possible from the users to the reference station or other central collection point. In this case the differential solutions are all calculated at a central location. This is often the case for test range applications where precise vehicle tracking is desired but the information is not used aboard the vehicle. The downlinked data can be position data plus the satellites tracked, or pseudorange and deltarange measurements, or it can be the raw GPS signals translated to an intermediate frequency. The translator method can often be the least expensive with respect to user equipment, and therefore is often used in munitions testing where the user equipment may be expendable.

10.3.4 Local Area and Wide Area Systems

The accuracy of a DGPS solution developed using a single reference station will degrade with distance from the reference station site. This is due to the increasing difference between the reference and user receiver ephemeris, ionospheric, and tropospheric errors. The errors are likely to remain highly correlated within a distance of 250 km, but such systems are often limited by the data link to an effective range of around 170 km. Such systems are usually called local area DGPS (LADGPS) systems.

DGPS systems that compensate for accuracy degradations over large areas are referred to as wide area DGPS (WADGPS) systems. They usually employ a network of reference receivers that are coordinated to provide DGPS data that is valid over a wide coverage area. Such systems typically are designed to broadcast the DGPS data via satellite, although a network of ground transmission sites is also feasible. A user receiver typically must employ special algorithms to derive the ionospheric and tropospheric corrections that are appropriate for its location from the observations taken at the various reference sites. The U.S., Canada, Europe, Japan, and Australia are planning to deploy WADGPS systems transmitting from geostationary satellites for use by commercial aviation. The satellites will also provide GPS-like ranging signals. Other nations may participate by providing clock corrections only from single sites or small networks, requiring the user to derive ionospheric corrections from an ionospheric model or dual-frequency measurements. Similar systems limited to military use have also been discussed.

Some commercial DGPS services broadcast the data from multiple reference stations via satellite. However, several such systems remain a group of LADGPS rather than WADGPS systems. This is because the reference stations are not integrated into a network, therefore the user accuracy degrades with distance from the individual reference sites.

10.4 SOLUTION ERROR SOURCES

The major sources of range error for nondifferential GPS are:

1. ***Selective Availability Errors***. Intentional SA degradations are applied to the GPS navigation signals to create the SPS level of accuracy. Two methods are used. The first method, called epsilon, alters the ephemeris (location) parameters of the satellite to give an apparent shift of satellite position. The second method, called dither, alters the satellite clock frequency, thereby introducing range errors in the C/A-code, P(Y)-code, and carrier signals. These errors resemble the naturally occurring ephemeris and clock errors.

2. ***Ionospheric Delay***. Ionospheric signal propagation delay can vary from 40-60 metres 95% by day to 6-12 metres 95% at night. This is a particular problem with a single frequency user (i.e., a single frequency C/A code set). Dual frequency receivers can correct for ionospheric delays with a residual error of some 4.5 metres 95%. The satellite navigation message contains correction coefficients for the single frequency user to reduce the ionospheric delay by appropriate algorithm.

3. ***Tropospheric Delay***. This signal propagation delay is caused by moisture in the lower atmosphere. Tropospheric delay may be up to 6 metres 95% in magnitude. Many receivers employ algorithms to minimize this tropospheric delay error.

4. ***Ephemeris Error***. This error is the difference between the actual satellite location and the position predicted by satellite orbital data. Normally, errors will be less than 8.2 metres 95%.

5. ***Satellite Clock Error***. This error is the difference between actual satellite GPS time and that predicted by satellite data. This error is normally less than 6.5 metres 95%.

DGPS can correct for the errors and induced biases listed above in the following manner:

1. ***Selective Availability Errors***. These errors are only of concern to the SPS user. They resemble the naturally occurring ephemeris and clock errors, except that they can be larger in magnitude and can change more rapidly. The epsilon error can be a three dimensional error. Therefore, part of the error will appear as a common range error and part will remain a residual ephemeris error. The residual portion is normally small and its impact remains small for similar look angles to the satellite. The dither error can appear as a time and frequency bias. This will be an error common to all receivers and will not be affected by signal propagation or distance from the satellite. However, since it is rapidly changing, any delay between the time of measurement at the reference station and time of use at the user receiver will result in a residual clock error. SPS DGPS systems are normally designed with a rate-of-change term in the corrections and rapid update rates to minimize this effect.

2. ***Ionospheric and Tropospheric Delays***. For users near the reference station, the respective signal paths to the satellites are close enough together that the compensation is almost complete. As the user to reference station separation is increased, the different ionospheric and tropospheric paths to the satellites can be far enough apart that the ionospheric and tropospheric delays are no longer common errors. Thus, as the distance between the Reference Station and user receiver increases the effectiveness of the atmospheric delay corrections decrease.

3. ***Ephemeris Error***. This error is effectively compensated unless it has quite a large out-of-range component (for example, 1000 metres or more due to an error in a satellite navigation message). Even then, the error will be small if the distance between the reference receiver and user receiver is small.

4. ***Satellite Clock Error***. Except in a satellite failure situation, this error is more slowly changing than the SA dither error. For all practical purposes, this error is completely compensated, as long as both reference and user receivers employ the same satellite clock correction data.

The correlation of the errors experienced at the Reference Station and at the user location is dependent on the distance between them, but they are normally highly correlated for a user within 350 km of the Reference Station. Table 10-1 shows the error budget for a PPS DGPS system, i.e., there is no added SA error. The error budget assumes that the common range error sources due to the Space and Control Segment are eliminated in a PPS DGPS system.

Table 10-1. PPS DGPS Error Budget

Segment Source	**Error**	**Normal Mode (m)**	**Differential Mode**	
			Near (m)	**Far (m)**
Space	Clock and Nav Subsystem Stability	6.5	0.0	0.0
	Predictability of SV Perturbations	2.0	0.0	0.0
	Other	1.0	1.0	1.0
Control	Ephemeris Prediction Model Implementation	8.2	0.0	0.0
	Other	1.8	1.8	1.8
User (P(Y)-Code)	Iono Delay Compensation	4.5	0	4.5
	Tropo Delay Compensation	3.9	0	3.9
	Receiver Noise and Resolution	2.9	4.1	4.1
	Multipath	2.4	3.4	3.4
	Other	1.0	1.0	1.0
UERE (95%)		13.0	5.8	8.3

Atmospheric errors can be eliminated if the user is close to the reference station, but if they are more than 250 km apart, the user will obtain better results using correction models for ionospheric and tropospheric delay. 250 km is a reasonable division between near and far. Table 10-1 above also shows how the reference station receiver noise and multipath errors are included in the differential corrections and become part of the user's error budget (root-sum-squared with the user receiver noise and multipath errors).

10.5 SYSTEM BLOCK DIAGRAM

Figures 10-2 and 10-3 show an example reference station and DGPS user equipment. Two receivers are shown at the Reference Station to increase the station reliability and to provide station integrity. Nominally each receiver will track all satellites in view in order to assure that differential corrections are determined for all satellites. With the full GPS constellation as many as eight to ten satellites may be in view. If eight satellites are visible, the reference station would have to broadcast data for 8 satellites. If SPS equipment is used, the broadcast can be unencrypted. If PPS equipment is used, the transmission of SA corrected errors requires the use of an encrypted data link.

From a military standpoint, DGPS no longer remains a passive system. DGPS transmitters have a limited range application (up to about 800 km). There will also be increased system cost for communications and processing equipment.

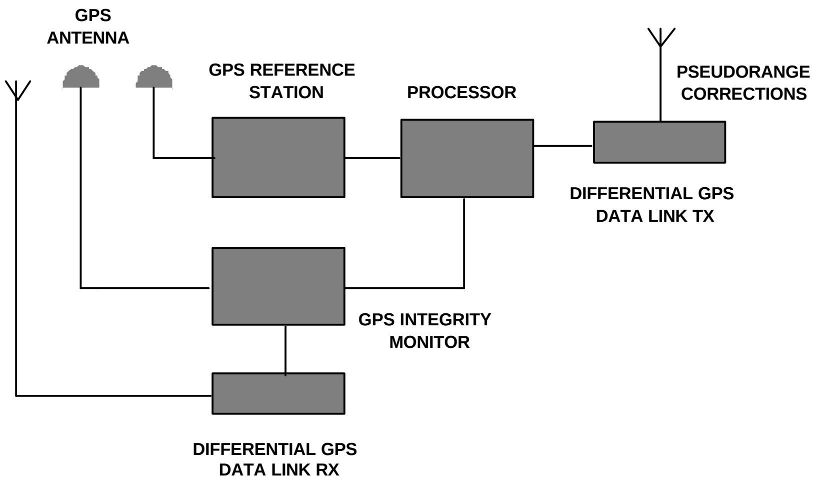


Figure 10-2. Typical Reference Station

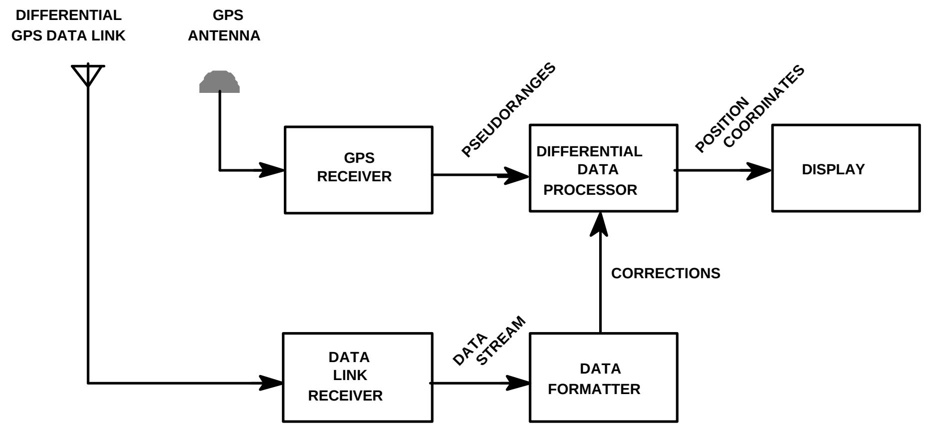


Figure 10-3. Typical UE Block Diagram

10.6 DGPS INTEGRITY

DGPS does more than increase positioning accuracy, it also enhances GPS integrity by compensating for anomalies in the satellite ranging signals and navigation data message. The range and range rate corrections provided in the ranging-code DGPS correction message can compensate for ramp and step type anomalies in the individual satellite signals, until the corrections exceed the maximum values or rates allowed in the correction format. If these limits are exceeded, the user can be warned not to use a particular satellite by placing "do-not-use" bit patterns in the corrections for that satellite (as defined in or RTCM SC-104 message formats) or by omitting the corrections for that satellite. Step anomalies will normally cause carrier-phase DGPS receivers to lose lock on the carrier phase, causing the reference and user receivers to reinitialize. User receiver noise, user processing anomalies, and multipath at the user GPS antenna cannot be corrected by a DGPS system. These errors are normally small and included in the overall DGPS error budget.

Errors in determining or transmitting the satellite corrections may be passed on to the differential user if integrity checks are not provided within the reference station. These errors can include inaccuracies in the reference station antenna location(s) that bias the corrections, systematic multipath due to poor antenna sighting (usually in low elevation angle satellites), algorithmic errors, receiver interchannel bias errors, receiver clock errors, and communication errors. For these reasons, DGPS reference station designs typically include integrity checking provisions to guarantee the validity of the corrections before and after broadcast.

In a local area DGPS system that provides integrity checks on the corrections at the reference station, Receiver Autonomous Integrity Monitoring (RAIM) may not be required in the user receiver when DGPS corrections are utilized in the position solution. As described above, the DGPS measurements/corrections ensure the integrity of the corrected measurements used by the user receiver. If the reference station validates the measurements/corrections sufficiently to guarantee the broadcast UERE, the only other place an integrity problem can occur is the user receiver. The user receiver can perform internal validity checks, other than RAIM, on its measurements and processing to detect any internal integrity problems. In a wide area DGPS system, RAIM may be useful to detect extreme ionospheric or tropospheric errors, if the desired differential accuracy can be degraded by these effects.

Information provided in a correction message includes the measurement time of each correction and the "Issue Of Data" (IOD) of the Ephemeris that was used to determine the corrections. It should also include a UDRE value for each satellite. The significance of these parameters is explained in the following paragraphs.

Most differential user receivers check the measurement times to automatically stop using reference station measurements (corrections) that exceed a predetermined age. DGPS position error increases as the measurement age increases because the reference station and user errors decorrelate with time. A user receiver propagates ranging-code corrections to the current time using the range rate corrections or propagates its own carrier-phase measurements to the reference station measurement time. This decreases the effect of the measurement age, but does not eliminate it. The major change in SPS measurements is due to SA. Consequently, the time for SPS measurements to become completely decorrelated is around two minutes. The major change in PPS measurements is due to satellite geometry. Therefore, PPS measurements can remain correlated for 10 minutes or more.

In order to maintain the integrity of a DGPS position solution, all corrections must be provided by the same reference station or by time-synchronized reference stations. This is because the correction values are dependent on the reference station clock. Mixing corrections from unsynchronized reference stations can generate unpredictable clock and range errors in the user receiver.

The corrections must also be based on the same IOD values that the user receiver is using. If the ephemeris data used to develop the corrections is different than the ephemeris data used in the user receiver, then the magnitude of the corrections will be invalid.

The UDRE is the differential equivalent of the URE for uncorrected satellites. It is a statistical measure of the expected residual range error after the corrections are applied. The correction UDRE values can be used in conjunction with the satellite geometry to calculate an estimate of the differential position error. The user receiver contribution to the total User Equivalent Differential Range Error (UEDRE) must also be considered in the position error calculations. (Different receivers can have different measurement errors.) If the reference station validates the broadcast UDRE values, the position error estimates can be used as an integrity check, much in the same way that RAIM is used by nondifferential receivers. That is, estimates of the user position accuracy can be periodically compared against the minimum mission requirements. The advantage of the differential method is that an overdetermined position solution (additional range measurements) is not required as in RAIM to maintain positioning integrity. If the number of available satellite corrections exceeds the number of tracking channels in the user receiver, these position error estimates can also be used to select the set of satellites that provide the most accurate position solution. Normally, the "all-in-view" position solution is most accurate, and the correction UDRE values are near the same magnitude. If one or more corrections have a relatively large UDRE, a subset of the satellites may provide a more accurate solution.

The standard maritime DGPS design, being implemented by several countries throughout the world, includes a differential user receiver located at a nearby surveyed site to serve as an integrity monitor. The integrity monitor receives and applies the corrections and develops a differential position solution in the same manner as any other user receiver. This position solution is then compared with the known antenna location. If the difference exceeds the allowed differentially-corrected position error, the transmission of all corrections is terminated. A message is also sent to the users warning them to stop using all previously transmitted corrections. Although this method protects well against large sudden errors, rigorous integrity is only provided for a user that determines a position using the same set of satellite corrections as the integrity monitor (typically the full set). Receivers that use only a subset of the satellites and transmitted corrections will have a higher DOP value for position determination and may have a significantly greater position error than the integrity monitor.

A more effective integrity method is to check the integrity of each individual correction in the range domain, rather than the position domain, providing integrity for users of any correction subset. This method also uses multiple receivers in the reference station (a minimum of two), but each receiver generates an independent set of corrections. The receivers also use different antennas, sited a sufficient distance apart that multipath effects are likely to be independent as well. The two sets of corrections are directly compared prior to transmission. The difference between each pair of corrections is a direct measurement of most of the components of the actual instantaneous differential range error seen by the user receiver. If a pair of corrections disagree by more than a predetermined amount, for example, 3 X UDRE (that is, 3-sigma UDRE), correction transmissions are interrupted for that satellite. In this way, the user does not receive or use any corrections until the integrity is checked, and the user can have confidence that the broadcast UDRE is a true measure of the expected range error. The reference station also has the ability to continue broadcasting the corrections that remain valid. This technique is particularly useful for applications that must meet short integrity warning times, must provide a highly confident estimate of UDRE, must minimize service interruptions, or that have slow correction transmission rates. Additional enhancements to this technique can include the use of dissimilar receivers to prevent common-mode errors within the reference station, the use of more than two receivers to "vote-out" anomalous measurements, or the calculation of an "average" correction between the reference station receivers.

Most of these integrity considerations apply equally to DGPS systems that base their corrections on SPS or PPS data. The primary difference is that the PPS corrections can be propagated for a longer time since the measurements are not influenced by SA-induced errors.

CHAPTER 11: SPECIAL APPLICATIONS FOR NAVSTAR GPS

11.1 INTRODUCTION

Navstar GPS is a positioning system that will be a definite force enhancer in military operations. Since GPS will also be available to civilian users and has the potential to enhance military operations other than weapon delivery, several special applications for GPS have been developed. This chapter will discuss four special applications already developed to indicate the variety of GPS uses. The four special applications discussed are as follows:

1. DGPS Applications
2. GPS used as an attitude reference system
3. Precise time and GPS
4. Orbit determination using GPS

11.2 DGPS APPLICATIONS

11.2.1 Potential Uses of DGPS

DGPS can be used for a variety of applications. Some of these applications will be discussed in this chapter.

- Instrument approach
- All weather helicopter operations
- Narrow channel maritime operations
- Reference Station for testing/calibration of navigation equipment
- Surveying for mapping and positioning
- Blind take-off

11.2.1.1 Instrument Approach

Most established airfields have sufficient landing instrumentation, however, during major conflicts, GPS can be used as an approach aid to temporary airfields. The GPS PPS accuracies are adequate to provide non-precision approach guidance to any landing location in the world, providing the coordinates of the runway end are accurately known. The use of DGPS would allow even better accuracy and may allow lower descent limits to a smaller landing area. The DGPS system can be set up almost immediately to provide very accurate guidance to any runway threshold.

11.2.1.2 All Weather Helicopter Operations

Helicopters are required to operate almost anywhere under all weather conditions, day or night. DGPS is used to give helicopters improved position and height information when maneuvering close to the ground and in close proximity to obstacles.

11.2.1.3 Narrow Channel Maritime Operations

There are two types of narrow maritime channels - natural confined waters and channels swept through mine fields. Large ships, both military and civilian, will operate in both types of narrow channels in wartime and will need all the position accuracy they can get. Use of DGPS will reduce the requirement for the width of the channel to be swept.

11.2.1.4 Reference Station for Testing/Calibration of Navigation Equipment

A Reference Station can provide the "ground truth" necessary for testing GPS and other navigation equipment. It can also be used to calibrate other terrestrial navigation system transmitters such as Loran-C and Omega.

11.2.1.5 Surveying for Mapping and Positioning

The use of DGPS to collect data for post-processing (not real-time DGPS) is a common operating method for mapping and geographical surveying purposes. The usual method is to use one mobile GPS receiver, one stationary reference GPS receiver, plus the necessary data recording and data processing equipment. The mobile receiver is moved around to those points that will be surveyed. GPS data (pseudoranges and deltaranges) are collected at both receivers and the actual DGPS process is done when the data from the two receivers is brought together at a later time. This technique eliminates the data link; despite this, very accurate DGPS data can be obtained within minutes of data collection.

11.2.1.6 Blind TakeOff

GPS is inherently most accurate in the horizontal plane. If the horizontal accuracy is enhanced by DGPS techniques, an aircraft could use the improved accuracy to navigate down a runway for take-off in zero/zero conditions.

11.2.2 DGPS Data Link

The transfer of data from the reference receiver to the mobile receiver can be done using any communication system capable of transferring digital data. It can be via telephone lines, radio or satellite communications. Military users of a data link may wish to consider encrypting the link to provide protection from imitation of the signal. Once the data is received, it can be loaded into the receiver by using existing interfaces such as the Instrumentation Port (IP), a MIL-STD-1553 data bus, or a special interface dedicated to DGPS data.

The use of pseudolites transmitting GPS NAV msg "look alike" data on L1 or L2 excludes the need for extra radio equipment on the user vehicle. The range of operation will also be very limited due to the high frequency of the pseudolite signals. The problem with pseudolites is that because of their high signal power relative to the received satellite signals, they can "jam" the user receiver if the receiver comes too close to the pseudolite. The user will then only receive the Reference Station (pseudolite) signals and not the satellite signals.

The solution to this problem is to transmit the pseudolite data in very short pulses so the user will appear to be "jammed" during short time intervals.

One proposed differential service is to broadcast GPS like data on L1 from geo-synchronous satellites. Compatible receivers would interpret these signals as an additional GPS satellite and read the differential correction data for all other satellites. The receivers would require a channel dedicated to receiving these corrections. This data link would provide coverage to wide areas of the earth and have the added benefit of providing additional satellite ranging methods to improve satellite availability.

11.3 GPS USED AS AN ATTITUDE REFERENCE SYSTEM

11.3.1 Introduction

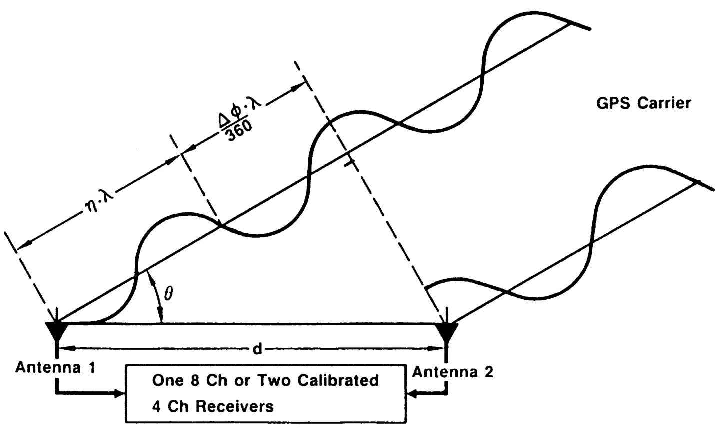
Angular orientation in 3 dimensions is frequently determined using inertial sensors. A GPS receiver with two or more antennas has the capability to be used for real-time angular reference.

Simulations and studies indicate that it will be cheaper and more accurate to use GPS for attitude reference than to use inertial sensors. Also, GPS attitude accuracy will not degrade with time. Combining GPS and inertial sensors for attitude reference would give the user the best of both worlds. Firstly, GPS will give very precise angular measurements under normal conditions and could provide updates to the inertial sensors, both for the wander in the gyros and the platform tilt error. Secondly, if the GPS receiver is jammed, the inertial sensors would still provide position, velocity and attitude. It could also be used to initialize the GPS receiver when the jamming is over.

11.3.2 Concept of Operation

The basic concept of operation for using GPS as an attitude reference system involves using various types of differencing techniques in conjunction with interferometry. Single differencing virtually eliminates the sensitivity of the antenna position errors to ephemeris, satellite clock, ionospheric and tropospheric error since they are common to both antenna positions. Double differencing eliminates the sensitivity to receiver clock biases.

A GPS interferometer measures the satellite carrier signal phase difference as it arrives at two different antenna locations. The two antennas, placed a distance "d" apart will receive the carrier signal at a different time and therefore with a different phase, see Figure 11-1.



d = Length of baseline
η = Number of whole wavelengths in phase difference between Ant_1 and Ant_2
$\frac{\Delta\phi}{360}$ = Wavelength fraction
λ = Carrier wavelength (L_1 or L_2)
θ = Angle between baseline and line of sight to the satellite

$$\theta = \cos^{-1}\left|\frac{\left(\eta + \frac{\Delta\phi}{360}\right)\lambda}{d}\right|$$

Figure 11-1. Interferometry Using GPS

The phase mismatch can be used to determine the relative orientation angle, *q*. Single differencing can be defined as taking the instantaneous difference in phase between the received signals from one satellite as measured at the two different antenna locations. Double differencing is obtained by differencing the single differences for one satellite with respect to the single differences for a second satellite. One interferometer can be used to determine the azimuth and elevation of the user. Two interferometers are required for 3-D attitude determination, (roll, pitch, and yaw).

The carrier wavelength ambiguity problem (determination of number of full cycles, n) can be solved by using the best estimate of position and attitude information for initialization, use of multiple satellites to provide additional geometric information, use of P(Y)-code to reduce the possible number of carrier wavelengths, and jointly processing on L1 and L2 carrier signals by the interferometer, known as widelanning.

11.3.3 3-D Attitude Reference System

3-D orientation requires at least 3 independent antennas to define a geometric plane. Four non-coplanar antennas could be used to define two planes and provide redundancy. Orientation solutions of the planes containing the antennas are related to the vehicle and therefore allow the orientation of the vehicle to be determined. The preferred method of operation is to get L1 and L2 frequency observations from four satellites continuously. This would require one 4-channel P(Y)-code receiver (or the equivalent) dedicated to each antenna. Optimum hardware for a 3-D attitude reference system is as follows:

- antenna subsystems
- 1 GPS 12-channel receiver

.

- Data processing unit
- Common reference oscillator

Another simpler alternative is to use one 8-channel P(Y)-code receiver and 3 antennas.

Four-channels would operate as a sub-receiver and would be dedicated to one master antenna. The sub-receiver and the master antenna read the NAV msg and provide position and velocity information for use when processing the signals from the other two antennas. This method can be used if the baselines between the antennas are sufficiently short to assume the position and velocity measurements are nearly the same for all three antenna locations. The two other antennas would only use 2-channels each to do carrier phase measurements on two of the four satellites that the "master" antenna was tracking. Which of the two satellites all three antennas would be tracking depends on the satellite geometry relative to the antennas. The technique requires that the measurement data is processed as if all satellite signals were received at the same time. Under high HV dynamics, the INS-derived angular information may be better than GPS.

11.3.4 Use of Multiple Receivers and a Reference Oscillator

When multiple receivers are used for interferometry it is recommended that a common external reference oscillator be used for all the receivers, otherwise the oscillators in each receiver must be calibrated. A common frequency reference would improve the accuracy of attitude measurements because all phase measurements would be done using the same time reference and thereby eliminate "own clock errors".

11.3.5 Error Sources and Degradation of Performance

The most dominant error sources are as follows:

- Absolute position uncertainty
- PDOP
- Antenna location
- Antenna position difference uncertainty in the body frame
- Measurement accuracy

11.3.5.1 Absolute Position Uncertainty

Errors in knowledge of the absolute position of the primary antenna can cause an angular orientation error in the local-level frame with which attitude is referenced. This orientation error transforms into an equivalent attitude error. Typical attitude errors of less than 0.03 minutes of arc can be expected.

11.3.5.2 PDOP

The attitude determination accuracy is influenced by the satellite geometry the same way as position accuracy. Poor satellite geometry results in less accurate position and attitude determination.

11.3.5.3 Antenna Location

Antenna location errors are a minimum when the two position difference vectors are orthogonal. Simulation results indicate that acceptable performance can be obtained when the vectors intersect at an angle between 45 degrees and 135 degrees. The performance deteriorates rapidly outside this domain.

11.3.5.4 Antenna Position Difference Uncertainty in the Body Frame

Uncertainty of the difference vectors in body-coordinates is a function of two primary factors: body flexure and errors inherited from the calibration process. Body flexure alters the relative position between antennas, hence causing errors.

11.3.5.5 Measurement Accuracy and Error Budget

The most significant factor influencing the feasibility of GPS attitude measurement is the accuracy of the range difference measurement. The error sources affecting accuracy are as follows:

1. Atmospheric delays
2. Multipath effects which can be quite significant, but can be largely negated by proper antenna placement
3. Phase difference measurement accuracy
4. Transmission delay stability

Very little is published about what accuracies can be expected when using GPS for attitude reference, but one manufacturer claims a heading accuracy of 0.3 degree, roll and pitch accuracy of 1.0 degree, updated at a 20 Hz rate with no practical speed limit, a maximum acceleration of 10 G, and a maximum angular velocity of 30 degrees/sec. The same manufacturer claims a heading accuracy of 0.05 degrees within 5 minutes in a stationary mode. This performance is with a C/A-code receiver, using 3 antennas placed in a triangle with 57 cm baseline between the antennas. Generally, the measurement accuracy depends on baseline length and measurement time. Longer baselines and longer measurement times will improve the accuracy.

11.4 PRECISE TIME AND GPS

11.4.1 Introduction

Precise time is important for a growing number of military, civilian, and scientific applications. Precise time references accurate to a few milliseconds or better have historically been complicated and costly to obtain, but GPS will afford the means to do it very simply and economically. Navstar GPS provides precise time, globally, to an absolute accuracy of approximately 200 nanoseconds (ns) relative to UTC (USNO). (This figure and others given in 11.3 and its subsections are subject to implementation factors and might be considered usual values; with careful implementations and under circumstances, much better accuracies are possible.)

11.4.2 Applications of Precise Time

Both scientific and civilian precise-time interests can be served by GPS. Some examples of civilian/scientific applications are described below:

1. Simultaneous observations of space objects from observatories

2. Use by national standards laboratories

3. Research into the theory of general relativity

4. Development and calibration of frequency standards

5. Use of Time Division Multiplexed (TDM) and other communications disciplines requiring precise time coordination between sites.

11.4.3 Interrelationship Between Different Definitions of Time

A number of different time definitions will be described here.

11.4.3.1 Time Based on the Rotation of the Earth On Its Axis

There are several definitions of time based on the rotation of the earth, but they are all interrelated (see Figure 11-2).

1. Universal Time (UT)

   UT is mean solar time on the Greenwich meridian. It is used in the application of astronomical navigation.

2. Universal Time 0 (UT 0)

UT 0 is determined directly from astronomical observations. It is non-uniform due to the irregular rotation of the earth on its axis and to polar motion.

3. Universal Time 1 (UT 1)

   UT 1 is UT 0 corrected for polar motion and is therefore more uniform than UT 0. UT 1 is the same as Greenwich Mean Time.

4. Universal Time 2 (UT 2)

   UT 2 is UT 1 corrected for mean seasonal variations and is therefore more uniform than UT 1.

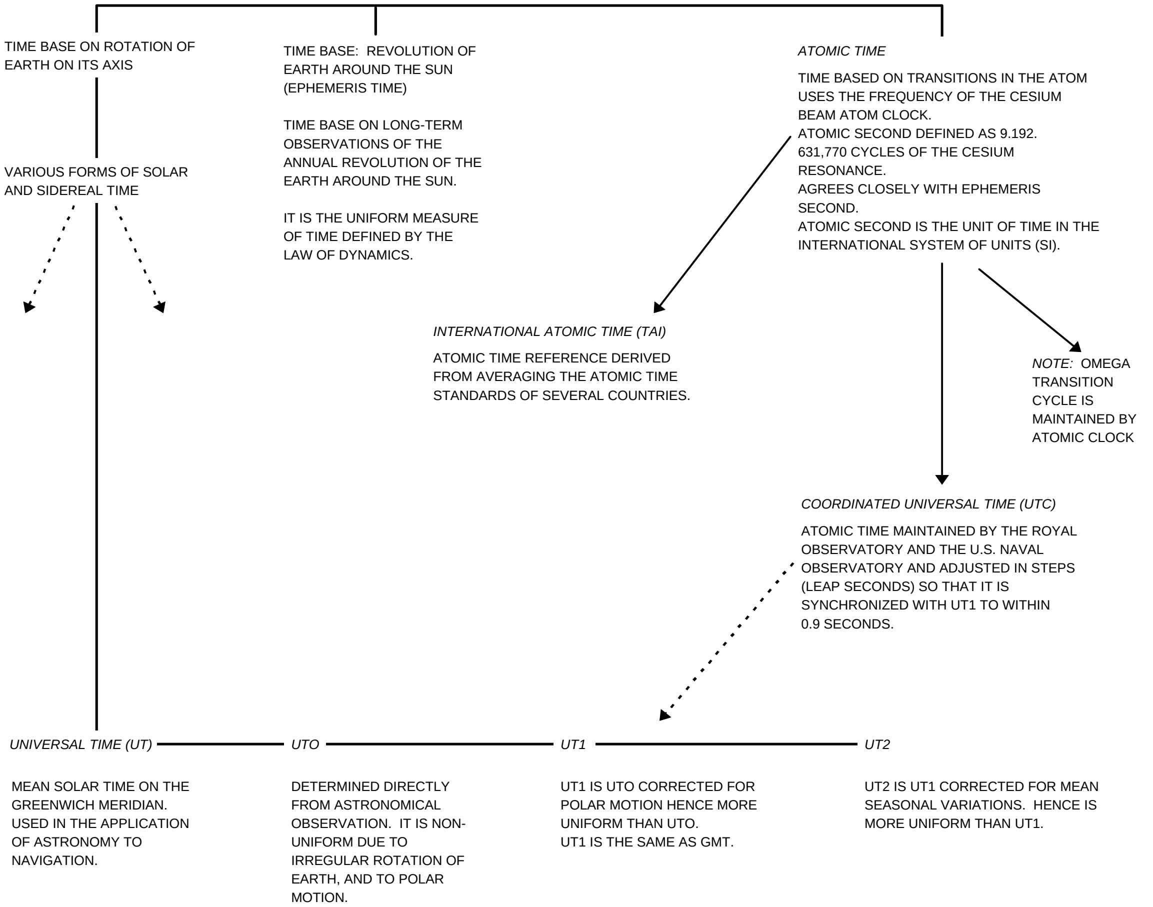


Figure 11-2. The Interrelationship of the Different Methods of Measuring and Defining Time

11.4.3.2 Atomic Time/UTC Time

Atomic time is based on quantified energy transitions within the atom. The atomic second is defined as 9192631770 cycles of the cesium resonance and is the unit of time used in International Systems of Units (SI). Atomic time is obtained practically by use of cesium beam clocks. However, no practical clock can be considered perfect at deriving the defined frequency. UTC is a type of atomic time maintained by the U.S. Naval Observatory (USNO), and others. UTC is occasionally adjusted in steps (leap seconds) to maintain agreement with UT-1 to within 0.9 seconds. Leap seconds are necessary because of the effects on UT-1 of the irregular rotation of the earth over time. The International Earth Rotation Service in Paris, France determines when step adjustments are necessary. A number of observatories/ laboratories maintain atomic clocks as very precise time references. They usually synchronize these clocks to UTC, which is the commonly used reference time. UTC represents an average of time from 58 different laboratories around the world. Each major country maintains its own version of UTC and defines national standards of time. Therefore, there is no one "Coordinated Universal Time". Instead, there is an International Atomic Time (TAI), kept in Paris by the International Bureau of Weights and Measures (BIPM), and several versions of UTC. The TAI is a weighted average of the times kept by the 58 laboratories which cooperate with BIPM to form this average. For the past few years, the majority of time comparisons used to form TAI have been done using GPS. The difference between TAI and the various national UTC time references are closely monitored and are therefore well known. National UTC references will therefore be steered to TAI when necessary and for GPS users, steering of UTC (USNO) will be experienced once every couple of years. For U.S. agencies, UTC is maintained by the U.S. Naval Observatory (USNO) in Washington, D.C. GPS time is required by the U.S. DoD to be referenced to UTC (USNO).

11.4.3.3 GPS Time

The internal reference time used by the three segments (Space-, Control- and User-Segment) in the GPS system is called GPS time. GPS time is a continuous time count, with no discontinuities, from the GPS epoch. GPS time is estimated and maintained by the MCS by estimating the ensemble satellite and monitor station time offsets. To aid USNO in providing a stable and accurate reference to the system, an ensemble of cesium-beam clocks is also maintained at the GPS Monitor Station that is collocated with the MCS. As a Precise Time Reference Station, it maintains time and rate very accurately traceable to UTC (USNO). It normally maintains a UTC (USNO) reference to an accuracy of a few nanoseconds. GPS time will normally be steered to within 30 nanoseconds of UTC (USNO) after accounting for the leap seconds which have accumulated in UTC since the GPS epoch of 0 hours 6 January 1980 (UTC). The remaining difference between GPS time and UTC (USNO) is transmitted in the NAV msgs from the satellites. The relationship between GPS time and UTC is:

GPS time = UTC time + DUTC time

where, DUTC time = Number of leap seconds + GPS-to-UTC bias

As of May 1995 the leap second difference between GPS and UTC is 10 seconds. The GPS receiver uses the NAV msg data to provide UTC (USNO) time outputs.

11.4.4 Precise Time Dissemination from GPS

GPS satellites have highly stable atomic clocks onboard with a known or predictable offset from GPS time. USNO monitors all the satellites when in view of the USNO in

Washington DC, U.S.A. and compares the GPS time and UTC (USNO) time transmitted by the satellites with the (USNO) Master Clock. Based on this comparison USNO determines the accuracy of the GPS/UTC time information provided by each GPS satellite and transfers this information to the MCS (see Figure 11-3). This GPS to UTC time bias and drift offsets, as well as the number of leap seconds, are uploaded in the satellite almanac data message. This information is used in the GPS receiver algorithms to determine UTC (USNO) time from GPS. The result is a world-wide time reference system for UTC (USNO) available to every user of GPS (see Figure 11-4). The absolute time accuracy available to the user depends on several factors described in Table 11-1, but the relative time accuracy between two GPS users can be much better than the absolute time accuracy. If the stations simultaneously track the same GPS satellites for time dissemination, then the effects of certain Control Segment and satellite-induced errors on the relative time accuracy are much reduced, and relative time accuracy can be as good as 10-20 ns. Almost all users employ local clocks or oscillators of some kind to satisfy system requirements for long- and short-term accuracy and stability, or to avoid the need for continuous updates from an external reference, such as GPS. Slaving the clocks too tightly to GPS time would impart to them the shorter-term instability associated with reception and interpretation of GPS signals and with the instabilities previously mentioned. Longer-term measurements that are required to obtain an accurate rate or frequency would not enjoy the short-term advantage of simultaneous tracking, since over a period of time, most of the space and Control Segment functions would effect the stability of the dissemination function.

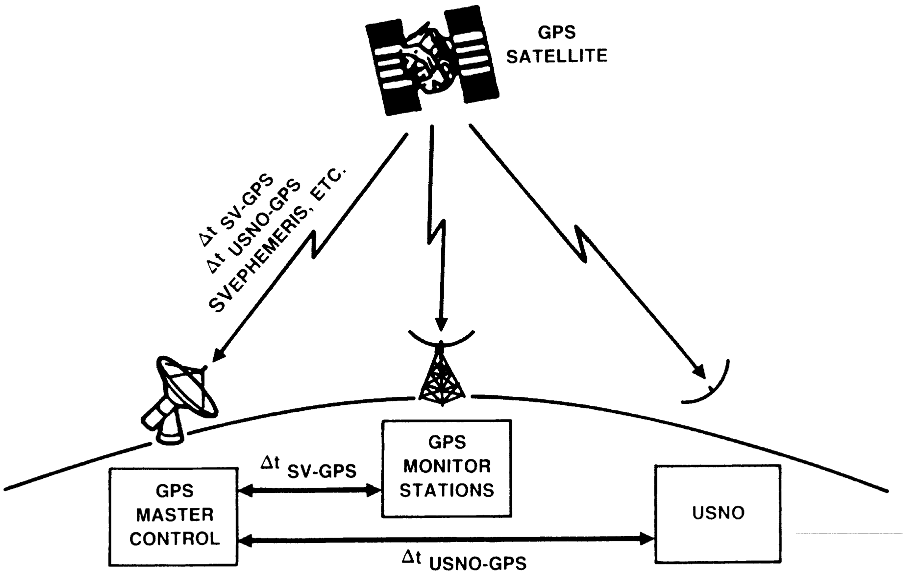


Figure 11-3. Determination of GPS-UTC (USNO) Time Difference

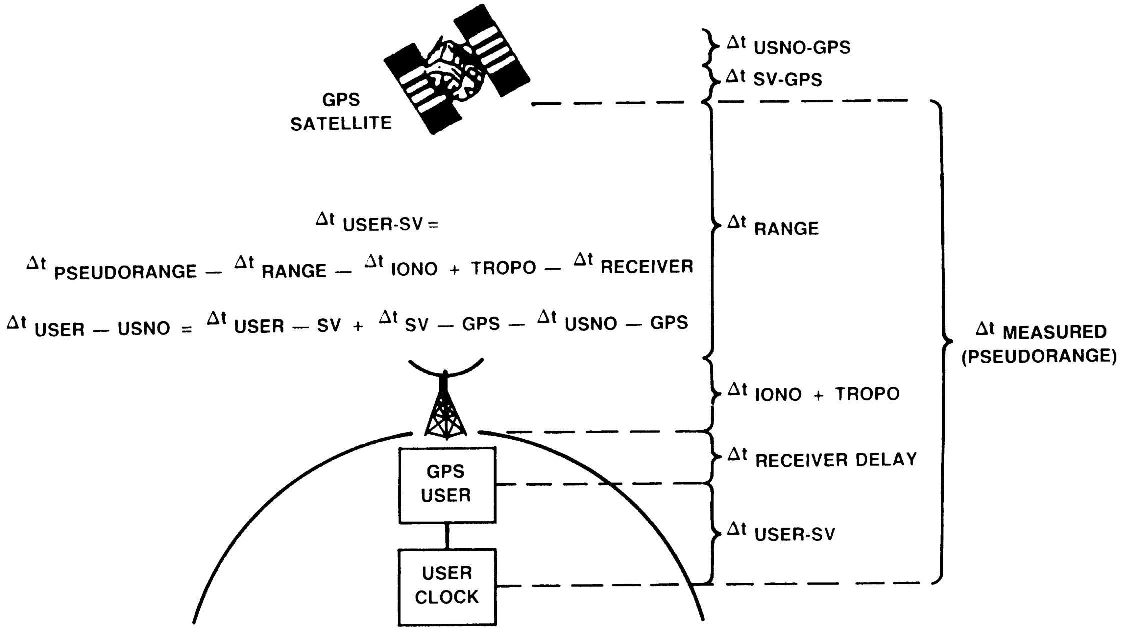


Figure 11-4. Uncoordinated Time Transfer Using GPS

Table 11-1. Uncoordinated Time Transfer Using GPS PPS Receivers

Error Source		C/A-Code		P(Y)-Code	
		Raw Measurements (ns, 95%)	Smoothed Measurements (ns, 95%)	Raw Measurements (ns, 95%)	Smoothed Measurements (ns, 95%)
SPACE	Frequency Standard Stability	22	22	22	22
	D-Band Delay Variation	3	3	3	3
	Space Vehicle Acceleration Uncertainty	7	7	7	7
	Other	3	3	3	3
CONTROL	Ephemeris Prediction Model Implementation	27	27	27	27
	Other	6	6	6	6
USER	Ionospheric Delay	33-65	33-65	15	15
	Tropospheric Delay	13	13	13	13
	Receiver Noise	58	10	58	10
	Multipath	8	8	8	8
	Other	3	3	3	3
	Position Error	144	144	144	144
TOTAL ERROR	Position Unknown	163-173	153-163	161	150
	Position Known	78-96	52-77	72	43
The values in the table are based on Table 3-1 "GPS System Error Budget" and the smoothing of the measurements is estimated to reduce the receiver noise by a factor of 6.					

To use the GPS time-dissemination service, one must track one GPS satellite (if in a precisely known location), or four GPS satellites (if in an unknown location). The absolute UTC accuracies that the user can expect are presented in Table 11-2 and depend predominately on the following:

- How accurately the receiver antenna position is known (if tracking 1 satellite)
- Whether a C/A- or P(Y)-code receiver is used
- Whether the user can "smooth" the measurements or has to use "raw" data.

Table 11-2. Coordinated Time Transfer Using GPS PPS Receivers

Error Source		**C/A-Code**		**P(Y)-Code**	
		Raw Measurements (ns, 95%)	**Smoothed Measurements (ns, 95%)**	**Raw Measurements (ns, 95%)**	**Smoothed Measurements (ns, 95%)**
SPACE	Frequency Standard Stability	0	0	0	0
	D-Band Delay Variation	0	0	0	0
	Space Vehicle Acceleration Uncertainty	0	0	0	0
	Other	0	0	0	0
CONTROL	Ephemeris Prediction Model Implementation	0	0	0	0
	Other	0	0	0	0
USER	Ionospheric Delay	0-65	0-65	0-15	0-15
	Tropospheric Delay	0-13	0-13	0-13	0-13
	Receiver Noise	58	10	58	10
	Multipath	8	8	8	8
	Other	3	3	3	3
	Position Error	144	144	144	144
TOTAL ERROR	Position Unknown	155-169	145-146	155-157	145-146
	Position Known	59-88	13-24	59-62	13-24
The values in the table are based on Table 3-1 "GPS System Error Budget" and the smoothing of the measurements is estimated to reduce the receiver noise by a factor of 6.					

11.4.4.1 Precise Time Dissemination Under Dynamic Conditions

Precise time accuracy degrades under dynamic conditions for two main reasons:

1. Temporary changes in the GPS receiver clock rate due to g-sensitivity

2. Reduced accuracy of the GPS receiver Kalman filter operation due to non-linear HV dynamics during each Kalman filter calculation cycle.

All oscillators are sensitive to accelerations. The requirement for a military GPS receiver's crystal oscillator is in the order of a maximum rate offset of 2 nanoseconds/second/g on two axes and a maximum of 3 nanoseconds/second/g on the third axis. If the receiver's measurement cycle is one second, a 4.5 g acceleration will therefore result in 9 nanoseconds of time error on one of the "better" axes. The Kalman filter in the receiver will also contribute with a time error due to the less accurate satellite tracking and therefore PVT dilution under dynamic conditions. This error is about 2 nanoseconds/second/g. The total time error under dynamic conditions is assumed to be approximately 20 ns greater than in the static mode.

11.4.4.2 Reduced Time Accuracy Due to SA

When SA is used by GPS, the pseudorange errors and therefore the position, velocity, and time errors will increase for a SPS receiver. This reduced pseudorange measurement accuracy will degrade the horizontal position to 100 m (95%).

The relevance for the time accuracy available from a SPS receiver is as follows:

1. 100 m (95%) horizontal position error is equivalent to 31.3 m UERE for each of the pseudoranges used in the navigation solution in the receiver.

2. A user in a known location using only one satellite for the time transfer will experience a time error of:

$$\frac{31.3}{3\text{x}10^8} \quad \frac{[\text{m}]}{[\text{m/s}]} = 104 \text{ ns } (1\sigma) = 204 \text{ ns } (95\%)$$

If the user is at an unknown location and uses 4 satellites, then his total time error due to geometry, SA and receiver errors will be:

104 ns * TDOP = 104 * 1.7 = 175 ns (Typical TDOP value)

SA will reduce the accuracy for SPS precise time dissemination to users of GPS, but the effect can be reduced by smoothing the time measurements. Also for SPS users, the relative timekeeping accuracy normally realized by observing the same satellites would be adversely affected by SA. The timing provided to them would be irregular, and their clocks would not be able to track it well. An alternative is to perform coordinated time transfer operations with USNO or another laboratory that maintains adequate traceability to UTC (USNO); because of the time-varying nature of SA, the coordination may need to be closer than it would under non-SA conditions.

11.4.5 Time Transfer Using GPS

Time transfers (clock comparisons) may be made in a number of ways using the GPS satellites. The time dissemination process described in paragraph 11.4.4 is a "passive" method, in which the user acquires an accurate time reference without having to transmit timing signals or data. Other ways that can provide more accurate comparisons are described in this section.

11.4.5.1 Coordinated Simultaneous-View Time Transfer

In this method, a pair of stations simultaneously observes the same satellite(s); then (through some communications medium) they exchange readings of their local clock time against the time disseminated by GPS. The difference between these readings is quite accurately the difference between the stations' clocks. The satellite clock is primarily a transfer clock and does not directly affect the time transfer accuracy. This method might be used where the user clocks are required to maintain time or frequency agreement more precisely than UTC can be disseminated through GPS. The method works particularly well when the participating clocks are located reasonably close together (within some hundreds of kilometers). The method can also substantially reduce the effects of S/A on time transfers made with the C/A-code, because both ephemeris and ionospheric effects are reduced. Unless the time transfer is made with USNO or a UTC(USNO)-traceable reference, the result is relative rather than absolute time accuracy.

11.4.5.2 Coordinated Simultaneous-View Time Transfer with USNO

USNO uses a coordinated simultaneous-view method as shown in Figure 11-5, to provide more accurate UTC(USNO) to certain Precise Time Stations within simultaneous-view range. Both USNO and the distant observer track the same GPS satellite(s), derive UTC (USNO) from the satellite's NAV msg and pseudorange measurements, and compare this time with the time maintained by their local atomic clocks. USNO compares UTC (USNO) derived from the GPS satellites with the USNO Master Clock. Thus, USNO can determine the Control Segment and Satellite- induced errors that the observer will have in his GPS-derived UTC(USNO). The distant observer can then correct his GPS derived UTC (USNO) with corrections received from USNO via a data link. Now the distant observer can correct his clock very accurately to serve as a local reference traceable to UTC (USNO). The time accuracies that can be obtained by this method are shown in Table 11-1. The Table 11-1 values are valid for time transfer using C/A-code only when SA is switched off. Smoothing of the time measurements brings the error down to what can be expected for a P-code receiver.

The errors due to ephemeris uncertainties and ionospheric delay usually cancel out of if the two receivers are close to each other. This is because they have nearly the same line of sight to the satellites, and the signals travel through the same part of the ionosphere. In some cases where the two receivers are close to each other, the use of both L1 and L2 to compensate for ionospheric delay will be less accurate than not correcting for ionospheric delay at all. This is due to the fact that dual frequency compensation for ionospheric delay is not perfect, and use of the ionospheric delay broadcast by the satellite by both parties produces more accurate results. For most cases where characters per second is used for coordinated simultaneous-view time transfer, the average of the values listed in Table 11-2 can be expected with distances of hundreds of kilometers between two receivers.

Compared with the uncoordinated simultaneous-view technique described in paragraph 11.4.4, coordinated time transfers with USNO can provide not only more accurate relative timing in the shorter term, but also better absolute timing and better long-term stability for setting and rating high-quality clocks.

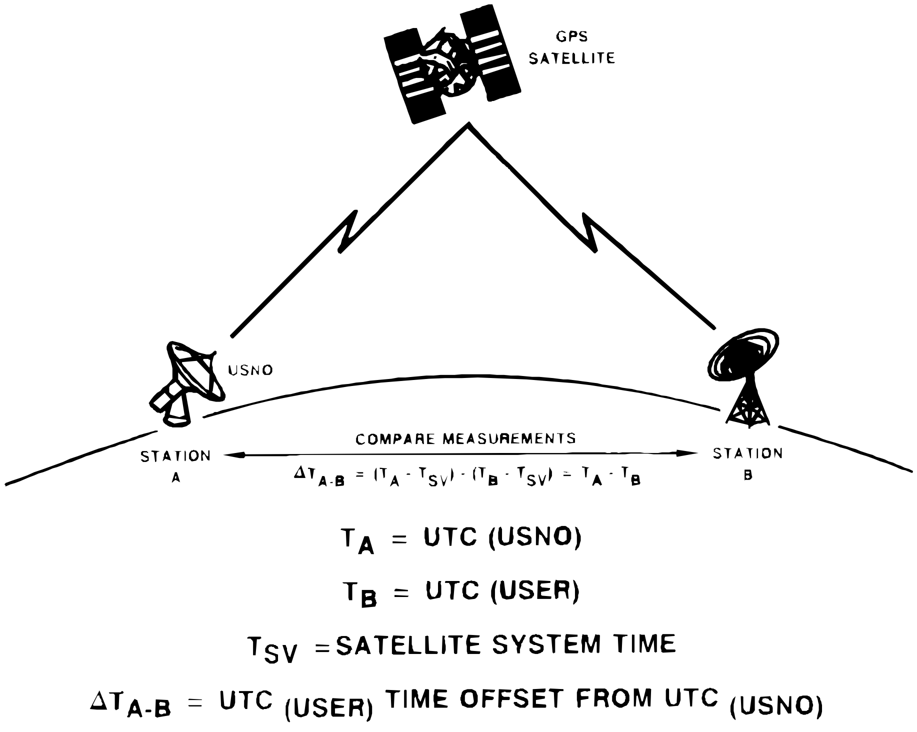


Figure 11-5. Coordinated Time Transfer using GPS

11.5 SATELLITE ORBIT DETERMINATION USING GPS

Precise satellite orbit determination can be done using GPS receivers on a satellite. These spaceborne GPS receivers must be specifically qualified for space use, because of the high temperature extremes and radiation levels. The space applications would be limited to low earth orbit satellites in order to receive adequate coverage from the half geosynchronous orbit of the GPS constellation. In addition to orbit determination, the spaceborne GPS receivers could be used to determine the spacecraft attitude. Preliminary studies and demonstrations have shown that using GPS for autonomous spacecraft position and attitude determination can be done cheaper and more accurately than some of the current methods.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 12: GPS INTEGRITY AND CIVIL AVIATION

12.1 INTRODUCTION

The civil aviation view of GPS is significantly different than that of most military users. The primary technical difference is that SPS C/A-code will be the only GPS signal available to most civil aviation users. Therefore, the civil aviation user must consider the reduced accuracy and statistical accuracy variations induced by SA. Consequently, civilian users are planning to use augmentations, for example, differential GPS, to improve the accuracy and availability of the SPS signals.

The primary difference in use of GPS is that civil aviation will use GPS almost exclusively for navigation and position reporting where safety-of-life is of tantamount importance. Therefore, integrity of the position solution is also of tantamount importance. Military users take a broader view of GPS as a force enhancement that will include peacetime as well as wartime operations and manned as well as unmanned missions. Therefore, military integrity requirements can vary widely depending on the mission, and can range, for example, from the extreme concern of safety-of-life for manned peacetime operations to lesser requirements for weapon effectiveness in a war-fighting environment.

Civil aviation also views GPS as a major component of a Global Navigation Satellite System (GNSS). The GNSS concept also includes the Russian Global Orbiting Navigation Satellite System (GLONASS), geostationary satellites broadcasting GPS- and/or GLONASS-like signals, and a possible international civil navigation satellite system. In this respect, it is likely that the civil aviation community will field systems that accept signals from more than one component of the GNSS to improve the overall accuracy, availability, and integrity of the civil positioning solution.

GPS and GNSS equipment for civil aviation will range from minimum-capability stand-alone receivers for general aviation users, to sophisticated integrated navigation systems for commercial users.

The primary benefit of GPS and GNSS from a Civil Aviation Authority (CAA) point-of-view is that GPS/GNSS has the potential to replace many existing ground-based radio navigation aids or obviate the need to procure new systems, thereby reducing the cost of maintaining or acquiring these systems. This is especially true for developing nations that do not have an extensive navaid infrastructure, and who could instead provide a regional integrity supplement to GPS (or GNSS) at a much lower cost than a traditional VOR navaid infrastructure.

The primary benefits of GPS and GNSS from a user point-of-view are potential fuel (cost) savings from more direct routing, improved (global) navigational coverage, and the potential to replace multiple navigation systems with a multi-use system. The primary concerns stem from the safety-of-life issue and the fact that GPS signal failures can affect large areas and consequently large numbers of aircraft simultaneously.

12.2 MILITARY USE OF NATIONAL AIRSPACE

Many NATO nations require military aircraft to meet civilian flight certification requirements and carry the necessary navigation equipments if they operate in controlled airspace without specific approval from the appropriate authorities. Military use of national airspace is usually a cooperative effort between the military services and the CAA of the particular nation. For example in the U.S., equipment, operational requirements, and flight certification are performed by the individual services, although some military aircraft maintain civilian flight certification and meet all civilian requirements. Military aircraft do not necessarily have the same integrity requirements as civilian aircraft, especially tactical aircraft that do not normally fly the civilian route structures intermingled with commercial and general aviation aircraft.

12.3 CIVIL AVIATION AUTHORITIES, AGENCIES, AND ORGANIZATIONS

12.3.1 Regulatory Authorities

The responsibility for establishing regulations and certifying the use of GPS in civil airspace is shared by the regulatory agencies of individual nations as well as cooperative efforts promoted by several multinational organizations. The primary regulatory agencies are the CAAs established by individual nations to regulate aviation within their own sovereign airspace. They have the ultimate authority and responsibility to manage air traffic and regulate aviation equipment, operations, and aircrews.

The International Civil Aviation Organization (ICAO) is a cooperative multinational organization that is the primary forum for establishment of Standards and Recommended Practices (SARPS) regarding international flights. ICAO is also the primary forum for international agreements to provide common standardized navigation and communication systems or address similar issues which ensure interoperability of systems, cooperation between nations, and generally promote flight safety and efficiency. The multinational agreements are supplemented by individual agreements between nations which can address such issues as joint use of both nations' airspace and mutual recognition of aircraft and aircrew certifications.

The European Organization for the Safety of Air Navigation (EUROCONTROL) is a multinational organization founded to promote flight safety in Europe. This region of the world has a particularly high density of international air traffic and close proximity of international borders, requiring a high level of cooperation between nations. Beyond air traffic management issues, EUROCONTROL has also become a focus for technical advancement of aviation systems in general.

12.3.2 Advisory Groups

There are two primary advisory groups charged with developing and recommending standards for the use of avionics systems in general and GPS/GNSS in particular. In the U.S., the Radio Technical Commission for Aeronautics (RTCA) has developed (and is continuing to develop) performance standards for airborne GPS/GNSS equipment. These standards have subsequently been incorporated into certification requirements by the U.S. CAA (the FAA). In Europe, the European Organization for Civil Aviation Electronics (EUROCAE) is performing a similar function for the European CAAs. Close cooperation between these two organizations has been maintained to ensure the viability of future international standards. Both organizations are voluntary and composed of representatives from government, industry, users, user groups, and related private organizations to allow broad participation in the standardization process.

12.3.3 Industry Groups

The Airlines Electronic Engineering Committee (AEEC) is a cooperative international organization of airline representatives that are developing common standards for the purchase of GPS/GNSS equipment and integrated systems. The standards focus on form, fit, and function of the equipment, rather than performance, and help minimize acquisition costs and maximize interoperability of similar systems. Equipment manufacturers and private organizations with an interest in the commercial aviation marketplace also participate in the committee activities.

12.3.4 Civil Aviation Coordination With the U.S. and U.S. DoD

Civil aviation activities and concerns are coordinated with the U.S. and U.S. DoD on several levels. At the international level, the U.S. is an active participant in ICAO in the development of international standards and policies and has offered GPS as a major component of the GNSS. Bilateral agreements have also been established between the U.S. and various nations to promote cooperation between the U.S. FAA and the various CAAs with respect to a variety of technical and policy issues. At the U.S. policy level, the U.S. DoT and U.S. DoD have jointly developed a Federal Radionavigation Plan (FRP) which serves as the planning and policy statement for all U.S. Government radio navigation systems. The FRP is updated every two years based on a review by DoT and DoD representatives and direct input from the public obtained through a series of radio navigation users' conferences. At the developmental level, the DoT is a direct participant in the GPS JPO and maintains a Deputy Program Director to represent civilian interests. At the operational level, the Civil GPS Service Steering Committee and the U.S. Coast Guard, via the GPS Information Center, distribute GPS operational information and coordinate civilian user concerns with the U.S. DoD U.S. Space Command and the GPS Control Segment.

12.4 PRIMARY CIVIL AVIATION CONCERNS WITH GPS

The primary civil aviation concerns with GPS are availability, accuracy, integrity, and liability. As mentioned above, a GPS signal loss or severe accuracy degradation can affect large areas and large numbers of aircraft simultaneously. For this reason civil aviation organizations have been strong advocates for maximizing the number of active GPS satellites in order to minimize the effect of losing any particular satellite signal, supplementing GPS with the other components of the GNSS, and providing an independent monitoring and warning system.

Integrity is defined in most references as the ability of a system to provide timely warnings to users when the system should not be used for navigation. From an operational point of view, the primary purpose of an integrity function is to detect navaid signal failures that would otherwise result in hazardously misleading navigation information (HMI) being displayed to a pilot or transmitted to an autopilot. Existing ground-based radio-navigation aids continuously monitor their output signals and typically shut down when a significant error is detected. Although the Control Segment and each satellite monitors GPS signal performance, the response time and fault monitoring has not been proved sufficient for civil aviation purposes. In addition, for SPS users, the accuracy degradation due to SA can occasionally result in position errors that are significant to some aviation uses, such as nonprecision approach. For these reasons an additional system or technique is required to assure GPS integrity.

12.4.1 Integrity Requirements

Integrity requirements for aviation are based on the general requirement to maintain safe navigation and avoid hazardous situations. Consequently, integrity requirements can be different for equipment with different purposes and can vary with phase of flight as the proximity to potential hazards changes. The key integrity parameters are the acceptable probability of a hazardous event, the navigation accuracy threshold that defines a hazard, and the allowed time delay before a warning must be issued. Requirements are most stringent when GPS is intended as the primary means of navigation under instrument flight rules (IFR). Requirements are correspondingly less stringent when GPS is intended as a supplementary aid to IFR flight, or a supplementary aid to visual flight rules (VFR) flight. In all cases, requirements also change based on the phase of flight. Requirements are most stringent when GPS is used for approach and landing, and correspondingly less stringent for terminal area and enroute flight, depending primarily on the dimensions of individual air traffic routes and/or aircraft spacing requirements. The allocation of integrity requirements to GPS can also vary if GPS is used in a hybrid system that performs automatic switching and/or cross-checking between different navigation sources. The following table shows an example of the ranges of integrity parameters. However, the promulgation of actual figures shall be given by ICAO.

Table 12-1. Typical Range of Integrity Parameters

Integrity Parameter	Typical Range
Acceptable Risk of HMI	10^{-5} to 10^{-7}/hr
Enroute Alarm Threshold	2 to 7 nmi
Terminal Area Threshold	1 to 3.5 nmi
Nonprecision Approach Threshold	0.3 to 1 nmi
Time to Alarm	6-30 sec
Availability of the Integrity Decision	95% to 99.999%
Acceptable False Alarm Rate	0.0003 to 0.00001/hr
Assumed Inherent Integrity of GPS	10^{-4} to 10^{-5}/hr
Required Fault Detection Rate	99.9%

It should be noted, that when integrity is a prime consideration, estimates of system accuracy and availability become dependent on the integrity methodology. The accuracy of a system becomes dependent on the accuracy estimate developed by the integrity methodology and used to compare against the accuracy threshold requirement. If the accuracy estimate is conservative, there will be a consequent loss of availability, since the system will be given less credit for accuracy than truly exists, and the comparisons against the accuracy thresholds will fail more often. Similarly, if additional measurements are required to make an integrity decision, the availability of the integrity decision can be significantly less than the availability of a navigation solution. In addition, to maximize availability and minimize prolonged periods of unavailability, if a faulty measurement is detected that affects integrity, it should then be excluded from the position solution, so that navigation can continue whenever possible using the remaining valid measurements.

12.4.2 Required Navigation Performance

As of this writing, there is a significant change beginning in the way navigation systems will be approved in the future. Historically, approvals to operate in a particular airspace or on a particular route or approach have been based on requirements to carry and operate specific types of equipment. The Required Navigation Performance (RNP) concept is to define navigation performance requirements for airspace, routes, or approaches and let the user demonstrate that equipment is provided aboard the aircraft that meets the applicable requirements. This is sometimes described as a "tunnel" concept, that is, RNP for a route would be defined in terms of an inner tunnel defined around the route centerline consisting of a 95% accuracy standard and an outer tunnel consisting of a 99.99% or higher accuracy standard. The outer tunnel is sometimes described as the "containment" tunnel, because that is a threshold beyond which a hazard is assumed to exist, typically described as a collision risk with another aircraft or the ground.

The parameters being considered to define RNP are accuracy, integrity, continuity, and availability. Continuity is defined as the probability that the navigation accuracy within a containment threshold will continue to be provided once an operation has begun. It is possible that integrity and continuity may have different levels of acceptable risk. In general, integrity faults are not obvious to the flight crew and do not give an opportunity to mitigate the situation. In contrast, loss of the navigation function is usually obvious to the flight crew, causing a heightened awareness and an opportunity to resort to alternate procedures. It is likely that the availability parameter will apply to the signals provided by the navaid infrastructure rather than the airborne equipment. It is assumed that the aircraft will not be dispatched unless the proper navigation equipment is available. Once the aircraft is airborne, the continuity requirement supersedes any availability requirement for the navigation equipment since the availability concept assumes the possibility of repair, which is generally not feasible in flight.

12.4.3 Integrity Assurance

The two primary approaches to assuring GPS integrity are autonomous integrity monitoring (AIM) and broadcast integrity messages (BIM). AIM, as the name implies, consists of analyses that the receiver or navigation system can perform autonomously or in conjunction with existing on-board navigation aids. Algorithms executed by the receiver are often called RAIM (Receiver AIM) and algorithms executed elsewhere in the aircraft are often called AAIM (Aircraft AIM). In the general sense, a Kalman filter is a form of AIM since it can detect and neglect certain types of anomalous measurements, however, it can fail to detect slow drift-type integrity failures. One common AIM technique relies on the principle that the receiver can in most cases detect and isolate a satellite signal failure that impacts integrity, if it has an overdetermined position solution. For example, if five satellite signals are available, five position solutions can be obtained using combinations of four satellites. In the event of a large pseudorange error in one satellite, the four solutions based on the faulty satellite will be similar to each other and significantly different from the fifth. In this case, the error can be easily detected and isolated. Much attention has been given to this subject by various researchers to evaluate and enhance the effectiveness of this technique. Similar techniques can be used to detect integrity failures using other sources of range or position information. Many of these techniques have been discussed in open literature, particularly in the papers of the various technical societies associated with navigation as well as the RTCA and EUROCAE.

The focus of recent AIM research has been primarily to enhance the availability of the integrity decision and enhance the probability of continuing with navigation after a fault has been detected. The primary methods of improving the availability of the integrity decision are to incorporate measurements from additional navigation sensors or to reduce the receiver mask angle to obtain more satellite measurements. The primary methods of improving the probability of navigation after detection are termed fault "isolation", fault "exclusion", and "partial identification". Fault isolation requires identifying the satellite which is broadcasting a faulty signal in order to remove it from the navigation solution. Fault exclusion is a slightly different technique which requires only that an offending satellite be excluded from the navigation solution when it is difficult to determine which of several satellites is faulty. Partial identification is a hybrid of the two

previous techniques which takes advantage of the strengths of both and appears to greatly improve the probability of continuing successful navigation.
BIM can take several forms, but is closely related to differential GPS/GNSS. In general, any system that provides differential GPS or GNSS corrections also provides BIM if it provides an assessment or guarantee of residual range errors after the differential corrections are applied to the receiver range measurements. The receiver can then estimate the residual position error using the observed satellite geometry and compare it against the current integrity alarm threshold. The BIM system can also make the integrity decision and issue use/don't-use messages for individual satellites, but there can be a significant increase in the false alarm rate for many users since the BIM system must make a conservative assumption regarding the user's satellite geometry and number of satellites in the user's position solution. Use/don't-use messages can still be valuable to indicate satellites that are not monitored or that are exhibiting extremely erroneous or erratic behavior.

BIM functions can be incorporated in either a local-area or wide-area differential system. The U.S., European nations, Japan, and Australia are currently planning or developing terrestrial networks of differential GPS/GNSS receivers with differential/integrity broadcasts via geostationary communication satellites. It is planned that the satellites will broadcast the messages superimposed on a ranging signal that emulates actual GPS ranging signals. These additional ranging signals will significantly enhance the availability of the SPS position solution in the coverage areas of the satellites. It is also likely that differential/integrity data may be broadcast by terrestrial stations in northern regions where geostationary satellite signals are intermittent or subject to obscuration. The U.S. and Canada are planning to have a cooperative wide-area system operating by 1998, and the European Community and Japan by the year 2000.

AIM and BIM can be supportive of each other, and may be used in combination to meet the most stringent integrity requirements. In addition, the U.S. DoD is implementing upgrades to the Control Segment monitoring and failure response time, to minimize the problem at the signal source. One such solution (nicknamed "satzap") involves commanding the satellite to change its PRN number to one that is unused, in the event a specific URE threshold is exceeded. The threshold would be chosen to protect non-precision approaches, which is the most restrictive integrity requirement for non-differential GPS. The unused PRN number would be permanently set unhealthy in the satellite almanacs so a properly operating receiver would never try to acquire it. Immediately after an upload, the failure response time would be extremely short since the ground antenna would already be in contact with the satellite. The technique would also be effective against slowly increasing errors (e.g., clock drift failures) since the satellite could be contacted and "zapped" before the error exceeded the URE threshold. Swiftly increasing errors and large step errors will normally cause a user receiver to lose lock. Fortunately, these types of errors can be easily detected by AIM, or a Kalman filter, in cases where a user receiver might acquire or reacquire the satellite before the control segment can correct or neutralize the problem.

CHAPTER 13: DIGITAL MAPS

13.1 INTRODUCTION

Maps serve a dual purpose for military use: for navigation and for tactical displays. Maps have traditionally been made from paper for navigation. Early digital maps could only show a subset of the data available on paper maps, such as roads. The maps and display units could not provide topographical, thematic or other information. Today, digital maps for navigation and tactical displays have been developed showing all the map information, that only paper maps could show previously. This chapter discusses digital maps and tactical displays, particularly with their relevance to GPS. Modern digital mapping and/or geographic information systems can easily relate data if the data has been geographically coded. Tools can be provided to locate all data points of a particular type within a particular region, calculate areas, distances, etc. ZOOM and SCROLL features can be used to more closely examine areas of interest, or eliminate extraneous information. Different types of data can be allocated to a unique layer, which can then be added or removed from the display as desired. Additional tools can be provided which make it easy to convert distances and measurement units from one format to another.

13.2 WHAT IS A DIGITAL MAP?

There are basically three types of digital maps today:

a. "Digitized" paper maps
b. Digital database maps
c. Hybrids

These maps are distributed in a variety of logical and physical formats. Physical formats include cartridges, CD-ROM, tape, and floppy disk. Logical data formats vary depending on the manufacturer. When selecting a digital map, be certain that the format is compatible with the software product that will be using the data.

13.2.1 Digitized Paper Maps

Digitized paper maps are not digital maps in the true sense. The digitized paper map is made by using an optical reader to "read" the information from a paper map, digitize it and store it in a database and then project the digitized paper map information on a video screen. There are two basic methods for storage of digitized paper map information: it can either be stored as vector information, or as raster information. The vector method is to define every point of a contour that shall be displayed on the map as a point on the end of a vector. Each vector will originate from a selected point on a map. The computer will "fill in" the open areas inside the contours with different colors depending on whether the contours are land masses, a navigation buoy, etc. This method requires the least data storage. In the raster storage method, an optional scanner scans the map and stores every bit of information from the paper map, including the "fill in" for contours. This method requires a much larger memory for map data storage than the vector method. These maps are no more accurate than the paper map, but are adequate for many applications.

13.2.2 Digital Database Maps

Digital database maps are maps presenting position data from a data base where all the position coordinates are collected through surveying operations. This information is therefore much more accurate and contains 3-D position data for every point on the map. Variations of this type of map are now available from various sources. Digital maps are often combined as overlays to digitized paper maps to provide a more accurate location of specific features such as roads, buildings, etc.

13.2.3 HYBRID Maps

Hybrid maps are combinations of digitized paper maps and digital database maps. Positioning coordinates that have been collected through surveying operations are used to 'adjust' the coordinates on the paper map. Distances between these benchmark points can then extrapolated by the display device. By using this technique, the digitized paper map can provide more accurate position information than the map it was prepared from, but it will still not provide the accuracy of a digital database map. The accuracy of these maps depends on the number and accuracy of the benchmarks employed, the accuracy with which they are combined with benchmark features on the digitized paper maps, and the accuracy of the extrapolation algorithms.

13.3 NAVIGATION MAPS AND TACTICAL MAPS

Maps normally serve two functions on board a military vehicle: they are used for navigation of the vehicle, and to give a visual display to the vehicle's commander of where enemy, friendly, and neutral forces are located. It also contains a geographical presentation of any other information of importance to the vehicle operators.

13.3.1 Use of Digital Maps for Navigation

Traditionally, navigation sensors (LORAN-C, TRANSIT, TACAN, DECCA, optical bearing, radar, etc.) have been used to determine position in latitude/longitude or bearing and distance from an object. The information was then transferred to a paper map to provide the navigator with information about his actual position relative to desired position. This information was then used by the navigator to decide the necessary course of action to get back to his desired track. For many military vehicles operating at high speed in confined waters/airspace during tactical engagements (radio communications, weapon delivery, etc.) positioning of the vehicle is a too time consuming process using traditional methods. Digital database maps with position and course/speed over the ground provided on the map by GPS are now being employed to provide the navigator/pilot with much more time to concentrate on other tasks without jeopardizing the vehicle's safety. GPS-derived latitude/longitude information presented on a CDU is too accurate to be utilized for positioning of the vehicle on a paper map using a pencil. The accuracy of the pencil mark (1 mm) on the map is only accurate to 50 m on a l:50000 map. Additionally, most of the navigator's problems are not related to the determination of the vehicle's absolute position, which is what the GPS CDU presents, but its position relative to obstacles, other vehicles, desired weapon release points, etc.

Only under en-route navigation is the navigator interested in his absolute position when navigating to pre-planned waypoints and/or rendezvous positions. The GPS derived position data must therefore be transferred to some kind of map to tell the operator where he is and where he wants to go. Position information from GPS displayed on a digital map can be verified by superimposing a radar picture on the digital map display or by presenting position information from other navigation systems on the digital map.

13.3.2 Use of Digital Maps for Tactical Displays

Tactical displays are often video screens or other displays which present a synthetic picture of target position and target course/speed obtained from external sources or onboard systems (electro-optical systems, lasers etc.). A radar picture can also be displayed on the same screen to provide a correlation between the radar picture and the synthetic picture. There are times when the radar may not be transmitting, for example, when Emission Control (EMCON) policies are implemented. During these times, compensation for HV movement is provided by an onboard navigation system such as an INS or gyro/log. Under such circumstances a digital map display has two limitations:

a. The synthetic picture "drifts" due to INS drift or inaccuracy in gyro/log information, if radar updates are not possible.

b. Only limited map information is available on the tactical display. Paper maps may have to be used to give a complete picture of the tactical situation.

These limitations can be eliminated by using digital maps updated by GPS. The tactical display picture then has no drift problem because it is constantly updated by GPS, where all map information including own position, course and speed are displayed very accurately. In additional to enhancing the performance of each individual platform, substantial improvements in multi-platform coordination are possible due to aligned tactical displays of the units.

13.3.3 Improvement of Common Reference Grids

The continuous availability of precise GPS position and velocity on participating platforms can provide numerous enhanced force coordination capabilities including:

a. Improved gridlock
b. Geodetic gridlock
c. Sensor calibration
d. Over The Horizon Targeting (OTHT) operations

13.3.3.1 Improved Gridlock

Gridlock alignment is often based on radar, LASER rangefinder or other sensor observations where bearing and range from a grid reference unit is transformed in grid coordinates of the force. This inter-platform alignment technique can introduce substantial errors in positioning if sensors are not correctly aligned. By incorporating a GPS receiver into the sensor, the inter-platform alignment can be greatly improved.

13.3.3.2 Geodetic Gridlock

Present gridlock algorithms provide a relative grid bringing participating units into relative alignment with respect to a common track, without regard to geodetic (absolute) position or orientation accuracy of the entire grid. While this serves current purposes well, advanced tactics and systems will require accurate geodetic as well as relative alignment of the grid. For instance:

a. Better incorporation of intelligence information (e.g. from other sensors/ subsurface, surface, air and space) using GPS as a common position reference system

b. Initialization of Long Range Sea/Land attack weapons

c. Maintenance of gridlock under EMCON conditions is a must for modern anti-air warfare systems where units are coordinated in fully automated way to respond to incoming threats.

13.3.3.3 Sensor Calibration

Improved alignment of search and fire control radar sensors and anti-submarine warfare sonar sensors by using GPS results in a more accurate weapon delivery.

13.3.3.4 OTHT Operations

In the OTHT arena, extended OTHT threat ranges have increased the necessity to hand off target track data to participating combatants at longer ranges which may not be gridlocked with the local tactical grid. Furthermore, many of the current OTHT exercises are conducted during radar EMCON where grid lock updates cannot be performed. Experience with Harpoon missile OTHT exercises has shown that significant relative navigation errors can occur under these circumstances and can lead to false target acquisitions and engagements between friendly forces. With GPS- equipped combatants, such problems can be eliminated and OTHT tactics can fully exploit the long-range intercept capability of modern surface-to-surface missiles. Use of digital maps, GPS and synthetic information on the tactical display gives the operator a complete picture of:

a. Own position/course/speed over ground (from GPS)
b. Accurate target position/course/speed

c. Friendly forces' position/course/speed
d. Geographical obstacles in possible weapon trajectories
e. Other information vital to the operator (safety zones, waypoints, weapon engagement zones, etc.).

13.4 OTHER ISSUES CONCERNING DIGITAL MAPS AND GPS

The use of digital maps and GPS raises at least three questions/problems to be aware of:

a. Electrical interfaces between GPS receiver and digital map systems
b. Digital map accuracy
c. Map datums

13.4.1 Electrical Interface Between the Digital Map Display and the GPS Receiver

Most of the available GPS receivers provide an external interface capability that can be used to integrate the receiver with a digital map system. These interfaces generally conform to the NMEA 0183 format. Differential receivers will also provide an RTCM SC-104 message. These interfaces may be usable to transfer GPS position, speed over ground, heading, etc. to the digital map. If you wish to integrate GPS with a digital map system, make sure that one or more of the GPS receiver interfaces are compatible with an interface on the digital map system in terms of:

a. Electrical characteristics
b. Functional characteristics
c. Data format
d. Data update rates

13.4.2 Digital Maps Accuracy

Digital maps that are produced by the raster-scan process from ordinary paper maps cannot be more accurate than the source documents from which they are prepared. Some of the paper maps used for navigation today are based on surveying data that is 80 to 100 years old. The quality of these maps leaves much to be desired when used for today's navigational needs. Additionally, inaccuracies in the optical reader system and operator-induced inaccuracies can produce errors which when combined are less accurate than the original paper map. It is therefore, very important to display the "age of the mapping data" on the digital map display to alert the navigator to the mapping inaccuracy.

13.4.3 Map Datums

The GPS receiver employs ECEF coordinates which are based on the WGS-84 map datum. Most receivers and digital mapping systems have the capability to convert from the WGS-84 datum to any one of a number of user-selected datums. When a

GPS receiver is integrated with a digital map it is important to ensure that the GPS receiver and the digital mapping system are configured for the same datum. If not, the navigation accuracy of the total system will be severely degraded.

ANNEX A: GLONASS: RUSSIAN'S EQUIVALENT NAVIGATION SYSTEM

This complete article was provided by
Mr. John Owen in 1995
and reflects the GLONASS situation at that date

A.1 HISTORICAL PERSPECTIVE

Similarly to the US TRANSIT, Russia operates CICADA, since the 1970's, the system consists of dual frequency VHF signals (150 MHz and 400 MHz) from satellites in near polar, low earth orbit. As the US has built up the Navstar GPS to replace TRANSIT, the Russians have developed an equivalent system, the Global Navigation Satellite Service, GLONASS. GLONASS uses a similar architecture to GPS for most components of its system users navigate with GLONASS in the same manner as GPS. The system saw its origins in the mid 1970s at the Scientific Production Association of Applied Mechanics (NPO PM) a developer of military satellite in Kransnoyarsk-26. Since 1982 a range of GLONASS satellites have been launched three at a time, from the Tyuratam space centre. Although there was some doubt concerning the Russians intentions in the early 1990's, however several statements concerning the systems future particularly to ICAO, and launches during 1994 and 1995 have confirmed GLONASS will reach full operation by late 1995.

GLONASS is owned and operated by Military Space Forces of the Russian Ministry of Defence. The Russian Institute of Radio Navigation and Time in St Petersburg designed and supports the synchronization of master clock systems, maintains satellite and Earth based time and frequency standards and develops receivers.

A.2 PURPOSE OF GLOBAL SATELLITE NAVIGATION SYSTEMS

GLONASS as Navstar GPS provides precision position fixing and time reference systems for world wide continuous use. An observer makes time-of-arrival measurements simultaneously to four satellites and by using the received data to compute the position of the satellites solves the four range equations for his three unknown position coordinates and time.

It is presumed the primary purpose of GLONASS is similarly to GPS for weapon system navigation and guidance. However as with GPS the wide interest in the use of satellite navigation systems has resulted in parts of the system being offered for international civil use.

A.3 SYSTEM ACCURACY

GLONASS produces both high accuracy signals specified as being for Russian military use only and a lesser accuracy signal for civilian use. The high accuracy channel is provide with an anti-spoofing capability Ref 1, that is controlled by the Russian Ministry of Defence. However, there is no equivalent of the selective availability deployed on GPS and currently the anti spoofing mode is not active, Ref 2.

Tests, Ref 2 of the GLONASS civil system have demonstrated accuracies of 30 m horizontally and 20 m in altitude and 0.05 m/s in velocity. However the specifications provided to the ITU, Ref 3 for GLONASS state a position accuracy of 100 m and a velocity accuracy of 0.15 m/s. Ref 1 refers to a horizontal accuracy of 100 m and a vertical accuracy of 150 m. A full GLONASS constellation provides a 94.7% probability of achieving the above accuracies worldwide. User derived time is within 1 ms of system reference time. Ephemeris accuracy to UTC is designed to be 5 ms. The Russians have classified the military accuracy of the system.

Recently a GLONASS Information Centre has been announced. The address is:

Mr V Gorev
Scientific-Information
Coordinate Centre
Military Space Forces
Kazakova ul.,23
Moscow 103064
Russian Federation
Fax: 7095 333-8133
Email: sfcsic@iki3.bitnet or sfcsic@mx.iki.rssi.ru#

A.4 MONITOR AND CONTROL SUBSYSTEM

As for GPS, GLONASS is controlled and monitored by a complex ground system. Data defining satellite position, system time and navigation message is uploaded to the satellites every 24 hrs with the satellite timing synchronized on every orbit, Ref 3 .

The GLONASS monitor and control segment consists of:

- Ground control centre (GCC) Moscow
- Central synchronizer (CS) Moscow
- TT&C stations Saint Petersburg, Yeniseisk, Komsomolsk-on-Amur
- navigation signal phase control system (PCS) Moscow
- quantum-optical station (QOS), Komsomolsk-on-Amur
- navigation field control equipment (NFCE) Moscow,Komsomolsk-on-Amur

The monitoring and control subsystem operate autonomously and receives the data of Earth rotation parameters, corrections to the system time relative to Russian Time & Frequency Standard (UTC SU) externally.

Satellite ephemeris is generated by observation of the ranging signals by the NFCE. However, GLONASS satellite also have a laser reflector that enables an independent measurement of range and orbit parameters.

A.5 SPACE SEGMENT

Satellite orbital position and the overall numbers in orbit are driven by the requirements for accuracy and availability. The constellation is made up of 24 satellites located in three orbit planes of eight satellites. The planes are spaced at 120 degree intervals around the equator and inclined at 64.8 degrees. (The longitude of the point where the satellite crosses the equation in a northerly directions is known as the Right Ascension of the Ascending Node, RAAN). The satellites are equally spaced in the orbit plane in circular orbits, maximum eccentricity 0.01, with a period around 11 hrs 15 mins at a height of 19100 kms. (These parameters are very near that planed originally for GPS before the 6 plane constellation was introduced).

It is reported Ref 1, that the constellation will be populated by filling pre-defined orbital "slots". Thus while the GLONASS system is being completed and when older satellites reach the end of their life, gaps will appear in the constellation. Based on the performance of all 24 satellite GLONASS controllers will determine the 'best' 21 to activate. The remaining three will be held back in reserve. Periodically the mix will be evaluated and if necessary a new best set of 21 defined. When necessary to maintain system accuracy three new satellite will be launched.

Taking plane 1 with an RAAN of 128 degrees on day 240, 1995 as reference, planes 2 and 3 have RAAN's of +120 and +240 degrees respectively as illustrated in Figure A-1. Separation in the argument of latitude or orbital phase in the plane is a multiple of 45 degrees. There is a displacement of +30 degrees and -30 degrees for satellites in planes 2 and 3 respectively with reference to plane 1. Phase angle is measured clockwise with the satellite direction of travel being anti-clockwise. Relative positions of satellites appear to remain stable over long periods. The rate of change of RAAN is approximately -0.03 degrees/day, resulting in the RAAN of plane 1 changing from 167 degrees in 1989 to 128 degrees in 1995.

All satellites have the same nominal orbital period of 11 hrs 25 mins. The orbit period is equivalent to a movement of 675.73 degrees of longitude, a change of 169.41 degrees W each orbit. The orbit produces a ground-track repeat every 17 orbits that is 8 days less 32.56 minutes. This diurnal offset of DT = 4.07 minutes from a full 24-hour day coincides with that of Navstar GPS and is very nearly the difference between a solar and sidereal day (3.93 minutes). This implies that each complete day less DT minutes a satellite performs 17/8 orbits or 2 whole revolutions plus an additional 1/8 revolution, equivalent to 45 degrees. Therefore two satellites in the same plane but separated by 45 degrees in orbital phase, appear at precisely the same position on successive days less DT minutes. Over a ground track repeat interval of 8 days, all satellites in the same plane with separation of 45 degrees appear in turn at the same position at intervals of 1 day less DT minutes. After 8 days, the whole cycle naturally repeats.

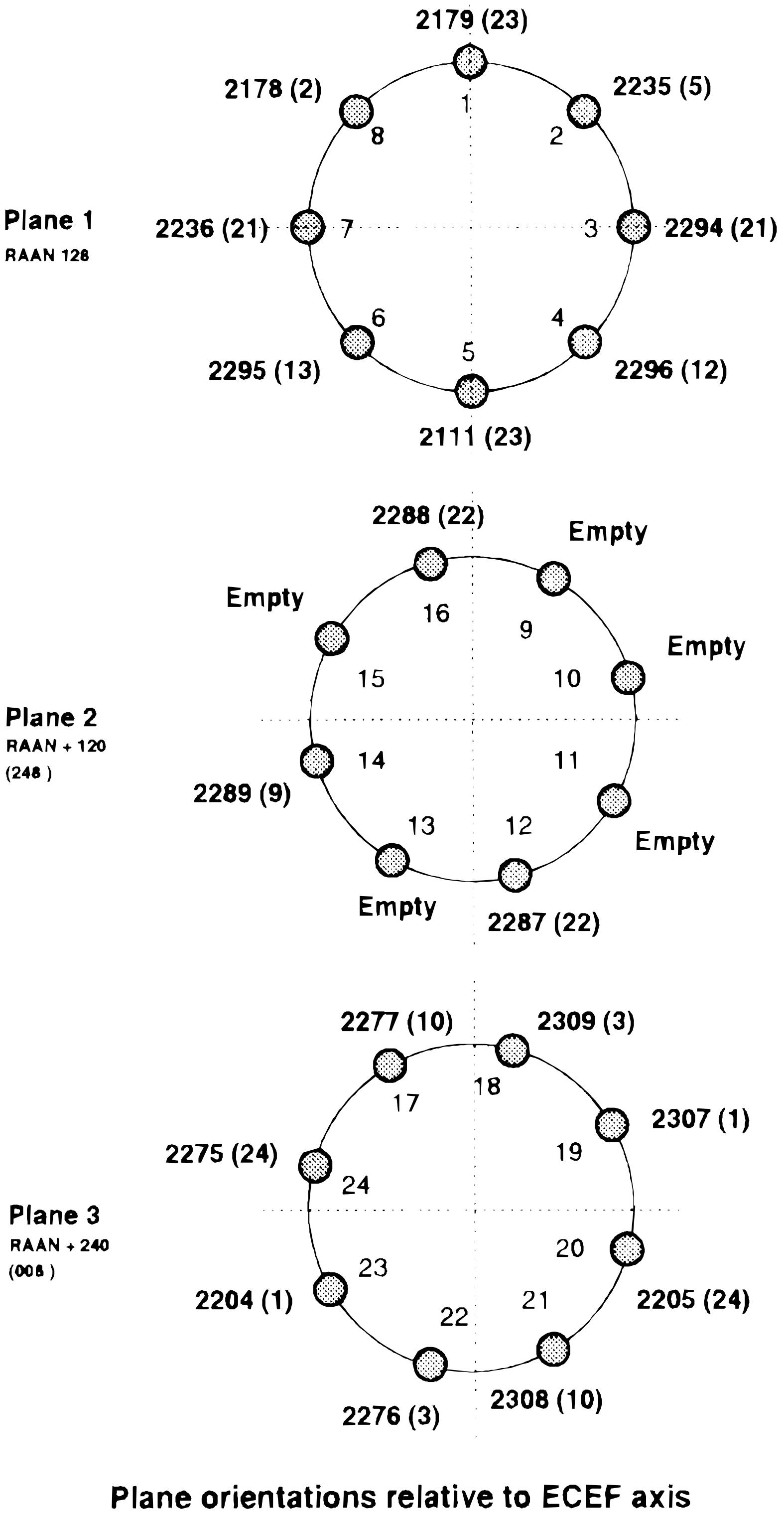


Figure A-1. GLONASS Orbit Planes and Slots

By examining the phases of satellites in the other planes 2 and 3, it becomes apparent that these satellites will also appear at the same position as the reference satellite in plane 1 within the same 8-day period. This arises because the time taken by the earth to rotate through the angle 120 degrees separating planes 1 and 2 is the same time taken by a satellite in that plane with phase +255 degrees to travel round to the same position as the reference satellite. The earth rotates through 120 degrees in 478.69 minutes, very nearly 8 hours, which corresponds almost exactly to 17/24 of a GLONASS orbit or +255 degrees. The same argument holds for plane 3 at 240 degree separation for a satellite at phase +150 degrees (or twice +255 less 360 degrees). The angular separation of 45 degrees within the plane together with the angular phase differences of +/- 30 degrees between planes assures that in an 8 day period, all 24 satellites will pass through the position with the reference sub-satellite location.

The above argument holds for any valid pointing angle. Once an antenna is pointed at any satellite in the system, all others will in time pass through the main beam. For any location, the azimuth and elevation for a particular track have to be computed over an 8-day period, following which suitable pointing angles and time may be chosen by the observer for the reference orbit and satellite. The entire subsequent orbital behavior is synchronous as explained. This argument has assumed a near-perfect circular orbit and precise orbital spacing and timing.

A.6 MANOEUVERING IN ORBIT

During recent years the Russians have moved several satellites within the orbital plane to a new position. This operation has occurred following a satellite failure or to position a particular satellites in antipodal positions to allow broadcast using common frequency. Manoeuvres to change the phase of a satellite in orbit begin by firing of the on-board thrusters at apogee where the velocity vector is at right angles to the radius vector. This action takes the spacecraft into an orbit with altered period (slightly eccentric) in such a way that the space-craft gradually falls behind or moves forward (depending on the direction of thruster firing) from its initial position. After an integer number of orbits, the required position in phase is reached and a reverse firing of thrusters of exactly the same magnitude as the first ensures a new stable and circular orbit. Taking the semi-major axis of the near-circular orbit as 'a' and the elliptical orbit as 'a-Da', then the eccentricity of the new orbit is 'e = Da/(a-Da)'. The change in orbital period DT, referred to the period of the circular orbit, is found from Kepler's third law :

$$\frac{\Lambda T}{T} = \frac{3}{2} * \frac{\Lambda a}{a} = \frac{m}{360n}$$

where

"n" integer number of orbits required to bring the satellite to the position in the circular

"m" degrees from its starting point.

An example of such a manoeuvre is provide by Daly, Ref 2. Cosmos 1885 was given a velocity change on 21 September 1987 such as to decrease its period by almost 8 minutes and then to carry out 21 orbits along the elliptical path, allowing the space-craft to accomplish the 90-degree phase movement in 10 days. It is clearly demonstrated that the GLONASS satellites are capable of rapid manoeuvering within the orbit. GLONASS spacecraft have enough fuel on-board to accomplish manoeuvres several times: Cosmos 1779 traversed 45-degrees of arc on three separate occasions. Clearly spacecraft in the orbital arc which fail can quickly be replaced by another spacecraft. This flexibility would give GLONASS an advantage during the operational phase where one would expect in-orbit spares to be in place and ready to cover for any malfunctioning units.

A different control philosophy appears to be used by the Russians to control GLONASS satellite to the US control of GPS. Whereas GPS satellites are precisely controlled to follow the same ground track each day, GLONASS does not repeat unlit 17 days. The result is that GPS appears to have a large number of control manoeuvres than GLONASS and must therefore carry more fuel and have a more complex control network.

A.7 SPACECRAFT DESCRIPTION

GLONASS spacecraft similarly to Cicada, have significantly shorter lifetime than US equivalents. Lifetimes have increased over the programmes life, see below, from under two years to currently approaching 5 years.

The Russians have announced that from 1995 a modified upgraded satellite will be deployed. There are several stages planned in the programme, Ref 1. The current GLONASS satellite has a mass of 1300 kg which will rise in 1995-8 to 1480 kg mostly due to increased fuel load. Minor modifications will be made to the Proton launch system with a reduction to two satellites per launch. Improvements will be made to the attitude control systems, clocks and ground systems. The result is an increase in navigation accuracy and time. In addition differential corrections with respect to Universal time and system time scales of GPS and GLONASS are planned to be transmitted.

The second stage of system development GLONASS-M is scheduled for deployment after 2000. (It is confusing that some Russian writers refer to the stage one upgrade as GLONASS-M). The upgrade will include autonomous satellite using inter satellite measurements to solve the ephemeris problem and improved lifetime for the solar arrays. Inter satellite measurements will be made in the optical and radio bands and communications provided for navigation data exchanges.Autonomous operation for 60 days without degradation is specified. The main error is caused by the extrapolation of the earth's rotation which are approximately 30 m/s RMS deviation in 60 days. The system is designed to produce users accuracies of 10 m, 0.01 m/s and 20 ns. The additional systems will increase the satellite weight to 2000 kgs.

The onboard clock is the most critical element of the satellite. GLONASS clocks of have seen a steady improvement in frequency and temperature stability from initially 5.10^{-11}, to better than 1.10^{-13} with operational lifetimes extending from 5000 to 18000 hrs. Future plans for GLONASS-M may include a Hydrogen Maser with a stability of 5.10^{-14}. Use of the H-maser is predicted to increase the operational accuracy of the system by an order of magnitude. An experiment is being conducted with Germany and Switzerland scheduled for a launch in 1995. Further development are planned before the H-maser are installed on GLONASS-M satellites in the 2000 + timeframe.

A.8 SATELLITE LAUNCH PROGRAM

The first GLONASS launch was announced in October 1982, although none of the three satellites became operational. GLONASS satellites are launched three at a time into the same orbit plane by the Proton launch vehicle. Initially successful launches were announcement within a day or two in Pravda, but recently the Russians have provided advanced notice of launches which have proved accurate to within a week.

By June 1995 there had been 59 satellite launched with currently 19 operational. Table A-1 presents the international identifiers, Cosmos numbers launch dates, end of operational life dates, orbit position and frequency. Initially all triple launches were into orbital planes 1 and 3, but in August 1994 the first launch was made into plane 2. Russia has now stated that the complete 24 satellite system will be operational by he end of 1996.

Many of the early launches produced only two or in some cases one operational satellite. The third satellite being a passive laser ranging target used to "... produce information for the increase in accuracy in the determination and prediction of motion of cosmic apparatus (satellites) ..." (Pravda, 2 June 1989). In this particular edition of Pravda also, the word GLONASS appears for the first time.

It was also a normal feature of the system in the early stages for a launch to occur only when the number of functioning satellites has fallen or was about to fall below the number required for adequate testing of the system. This number cannot be stated with absolute precision since it depends on the orbital planes of the remaining satellites. However a reduction of available units to any number less than four was likely to act as a precursor to a new launch.

Table A-1. GLONASS Satellite Launches

COSMOS No	**SCC**	**Launch Date**	**End Date**	**Orbit Slot**	**Ch No**	**L1 (MHz)**	**L2 (MHz)**
1413 **	13603	Oct 82	Jan 84	-	-	-	-
1490 **	14258	Aug 83	Aug 84	03	3	1603.6875	1247.3125
1491	14259	Aug 83	Oct 83	02	1	1602.5625	1246.4375
1519 **	14590	Dec 83	Sep 84	-	18	1612.1250	1253.8750
1520	14591	Dec 83	Jan 86	18	2	1603.1250	1246.8750
1554 **	14977	May 84	Aug 85	19	9	1607.0625	1249.9375
1555	14978	May 84	Oct 85	18	24	1615.5000	1256.5000
1593 **	15259	Sep 84	Nov 85	-	10	1607.6250	1250.3750
1594	15260	Sep 84	Sep 86	-	-	-	-
1650 **	15697	May 85	Jun 86	01	7	1605.9375	1249.0625
1651	15698	May 85	Jun 86	-	10	1607.6250	1250.3750
1710 **	16396	Dec 85	Feb 87	18	4	1604.2500	1247.7500
1711	16397	Dec 85	May 87	17	19	1612.8675	1254.3125
1778	16961	Sep 86	Feb 87	02	11	1608.1875	1250.8125
1779	16962	Sep 86	Jul 88	01	20	1613.2500	1254.7500
1780	16963	Sep 87	Jun 88	08	22	1614.3750	1255.6250
1838-9-40	17902	Failed	Launch	-	-	-	-
1883	18355	Sep 87	Jun 89	17	14	1609.8750	1252.1250
1884	18356	Sep 87	Aug 88	17	21	1613.8125	1255.1875
1885	18357	Sep 87	Jan 89	24	5	1604.8125	1248.1875
1917-8-9	18857	Failed	Launch				
1946	19163	May 88	May 90	08	12	1608.7500	1251.2500
1947	19164	May 88	Mar 91	07	23	1614.9375	1256.0625
1948	19165	May 88	Jun 90	01	24	1615.5000	1256.5000
1970	19501	Sep 88	May 90	17	18	1612.1250	1253.8750
1971	19502	Sep 88	Aug 89	20	7	1605.9375	1249.0625
1972	19503	Sep 88	Nov 91	18	10	1607.6250	1250.3750
1987	19749	Jan 89	Mar 93	02	9	1607.0625	1249.9375
1988	19750	Jan 89	Jan 92	03	6	1605.3750	1248.6250
2022	20024	May 89	Jan 90	19	16	1611.0000	1253.0000
2023	20025	May 89	Nov 89	24	17	1611.5625	1253.4375

** Three satellite launch only two reached operation

Table A-1. (Cont) GLONASS Satellite Launches

COSMOS No	SCC	Launch Date	End Date	Orbit Slot	Ch No	L1 (MHz)	L2 (MHz)
2079	20619	May 90	May 94	17	24	1615.5000	1256.5000
2080	20620	May 90	Aug 94	19	3	1603.6875	1247.3125
2081	20621	May 90	Aug 92	20	15	1610.4375	1252.5625
2109	21006	Dec 90	May 93	04	4	1604.2500	1247.7500
2110	21007	Dec 90	Mar 94	07	13	1609.3125	1251.6875
2111	21008	Dec 90	op	05	23	1614.9375	1256.0625
2139	21216	Apr 91	Aug 92	21	20	1613.2500	1254.7500
2140	21217	Apr 91	Nov 94	22	11	1608.1875	1250.8125
2141	21218	Apr 91	Feb 92	24	14	1609.8750	1252.1250
2177	21853	Jan 92	Mar 93	3	22	1614.3750	1255.6250
2178	21854	Jan 92	op	08	2	1603.1250	1246.8750
2179	21855	Jan 92	op	01	23	1614.9375	1256.0625
2204	22056	Jul 92	op	24	1	1602.5625	1246.4375
2205	22057	Jul 92	op	21	24	1615.5000	1256.5000
2206	22058	Jul 92	Jun 94	20	8	1606.5000	1249.5000
2234	22512	Feb 93	Mar 94	03	12	1608.7500	1251.2500
2235	22513	Feb 93	op	02	5	1604.8125	1248.1875
2236	22514	Feb 93	op	06	21	1613.8125	1255.1875
2275	23043	Apr 94	op	17	24	1615.5000	1256.5000
2276	23044	Apr 94	op	23	3	1603.6875	1247.3125
2277	23045	Apr 94	op	18	10	1607.6250	1250.3750
2287	23203	Aug 94	op	12	22	1614.3750	1255.6250
2288	23204	Aug 94	op	16	22	1614.3750	1255.6250
2289	23205	Aug 94	op	14	9	1607.0625	1249.9375
2294	23396	Nov 94	op	3	21	1613.8125	1255.1875
2295	23397	Nov 94	op	6	13	1609.3125	1251.6875
2296	23398	Nov 94	op	4	12	1608.7500	1251.2500
2308	23511	Mar 95	op	22	10	1607.6250	1250.3750
2309	23512	Mar 95	op	19	3	1603.6875	1247.3125
2307	23513	Mar 95	op	20	1	1602.5625	1246.4375

Op: Operational June 1995.

A.9 TRANSMISSION FREQUENCIES

The carrier frequency chosen to transmit the L1 navigation signal are in the ITU assigned aeronautical satellite navigation band from 1559 MHz to 1620 MHz. A dual frequency system is used for the precise military signal with a second L2 transmission in the 1250 MHz band. Dual frequency navigation messages at L1 and L2 allow the user to correct for ionospheric propagation effects and are incorporated into both NAVSTAR and GLONASS.

Unlike GPS GLONASS uses a different frequency for each satellite. Radio frequency carriers used by GLONASS are channelized within the bands 1240-1260 MHz and 1597-1617 MHz, the channel spacing being 7/16 or 0.4375 MHz at L2 and 9/16 or 0.5625 MHz at L1. The carrier frequencies are multiples of channel spacing. Currently the number of planned channels is 24 but the Russians have given notice, Ref 4, that this is scheduled to change in the late 1990's to 12 with anti podal satellites transmitting at the same frequency, see Fig A-1.

The frequency is defined from the following expressions.

$$L1(f) = 1602.2 + 0.5625 K MHz$$

$$L2(f) = 1246.0 + 0.4375 K MHz$$

where:

K = ± 0,1,2.......24 the carrier number

K = 0 is reserved for test purposes and is not used operationally.

All frequencies in each of the L1 and L2 bands are coherent and formed by the same frequency standard. The ratio of frequencies (K2/K1) emitted by a satellite in L1 and L2 is 7/9. The frequency used by particular satellites is transmitted in the almanac transmitted by each satellite in the constellation. Initially all GLONASS satellites used a separate frequency. However, since 1992 the Russians have begun to use common frequencies for anti-podal satellites.

Following the World Administrative Radio Conference in 1992 the Russians have announced their intention to move the GLONASS frequency Band. At WARC-92 coprimary allocations were given for Radioastronomy, 1610 to 1613 MHz and for Mobile Satellite Systems (ground to satellite) 1610 to 1620 MHz. From 1998 to 2005 the Russians have stated GLONASS will use the frequency band 1598.0625 MHz (K=-7) to 1609.3125 MHz (K=13) for L1 and the equivalent frequencies 1242.9375 MHz to 1251.6875 MHz for L2. After 2005 GLONASS will use frequency channels K= -7 to K= +4 with channels 5 and 6 used for technical operations (K (6) = 1605.3750 MHz L1 and 1248.6250 L2).

A.10 TRANSMISSION POWERS AND PROTECTION RATIO

The power radiated by each satellite is defined in Table B-2 for various angles from the boresight of the transmitting antenna. The power flux density at the earth's surface for satellites at greater than 5 degrees elevation submitted to the ITU, Ref 4 are as follows:

-152 dBW/m^2 per 4 KHz - for C/A-code signals in L1 band

-162 dBW/m^2 per 4 KHz - for P-code signals in L1 band

-168 dBW/m^2 per 4 KHz - for P-code signals in L2 band

The power output from a 0 dBic antenna is specified as :

-160 dBW for C/A and P-code L1.

-166 dBW for P-code L2.

However, measurements of the signal strength suggest that the L1 GLONASS C/A code is 2 to 3 dB stronger than GPS. The Russians have defined a protection ratio (wanted signal power to maximum tolerable interference) for the GLONASS signals as:

-15 dB for C/A code in L1 band

-25 dB for P-code L1 and L2 bands.

GLONASS specify that a satellite in an adjacent frequency allocation shall not create interference above -48 dB if visible.

Table A-2. GLONASS Transmitted Power

e, degrees	0	15	19	Notes
EIRP, dBW	25	27	23	For narrow and wide band signals in L1 band
EIRP, dBW	19	21	18	For wide band signals in L2 band

A.11 INFORMATION TRANSMISSION, BANDWIDTH AND CODE RATES

Each satellite transmits a navigation signal in the L1 band that includes two pseudo noise signals, modulated by Biphase Shift Keying onto the carrier separated by a 90 deg phase shift. The chip rate of the pseudo random sequences are 0.511 MHz (C/A-code) and 5.11 MHz P-code. Each satellite also transmits the P-code at 5.11 MHz on the L2 frequency. The Russians have stated the P-code is not included in the civil system offered for general use.

The BPSK modulation produces the classical $\text{sinc}^2 x$ (sinc x = sin x over x) spectrum centred on the carrier frequency with nulls at multiples of the bit rate. The signal appears to be filtered before transmission to limit the transmission bandwidth to only the first two nulls. A typical spectrum is illustrated in Fig A-2. Some GLONASS satellites, but not all have been observed, Ref 2, to contain additional spectral lines precisely at the spectral nulls of +/- the code rate.

Two theories have been put forward to explain the appearance of spectral lines at code nulls. The first postulates that the lines are present by accident as a result of poor implementation of the carrier modulation circuitry. An alternative theory that the lines were deliberate in order to provide instantaneous satellite velocity information has not been substantiated. The occurrence of the phenomena has been intermittent, GLONASS 19 and 20 had very pronounced lines. No lines have been observed on any of the satellites launched during 1986-1988 but they have reappeared on satellites launched in 1989 (GLONASS 42).

A.12 RANGING CODES

GLONASS employs ranging codes similar to GPS, but with the same code transmitted by all satellites at different frequencies. The equivalent of the GPS C/A code uses a maximum length sequence with a period of 1 ms and a bit rate of 0.511 Mchips/s, a length of 511 bits as compared to the GPS C/A code of 1023 bits, Ref 5. The code is generated by a feedback 9 element shift register, (2^9 -1 = 511bits) with feedback from the 5th and 9th taps. The output is taken from the 7th tap.

The P code appears to be a truncated maximum length sequence generated by a 25 -bit shift register with feedback from the 3rd and 25 taps. A maximum length code from such a generator has a length of 2^{25} -1 = 33554431 bits. At a clock rate of 5.11 MHz the code would be 6.5664 seconds, but the sequence is short cycled at the second boundary and the register reset to all ones.

A.13 NAVIGATION DATA

Navigation data is transmitted at 50 baud, Ref 6. In common with GPS, the data is formatted into frames, sub-frames and words. A frame has a duration of 150 seconds and is sub-divided into five sub-frames. Each sub-frame is divided into 15 lines, of 2 seconds duration. The first part of each line 1.7 seconds duration contains a preamble (always 0), line number (4 bits), data parameters (72), parity bits (8). The C/A code navigation data includes a 'meanda' code at double chip frequency 100 Hz, 0101010.... is modulo 2 added to the data, resulting in a 'Manchester' modulation. The remaining 0.3 seconds is composed of a time mark at 100 Hz, 111110001101110101000010010110, the last bit is aligned with even integer seconds from the beginning of the day Moscow time UT(SU). P-code navigation data is a non return to zero 50 baud data message with several differences from the C/A code Ref 7.

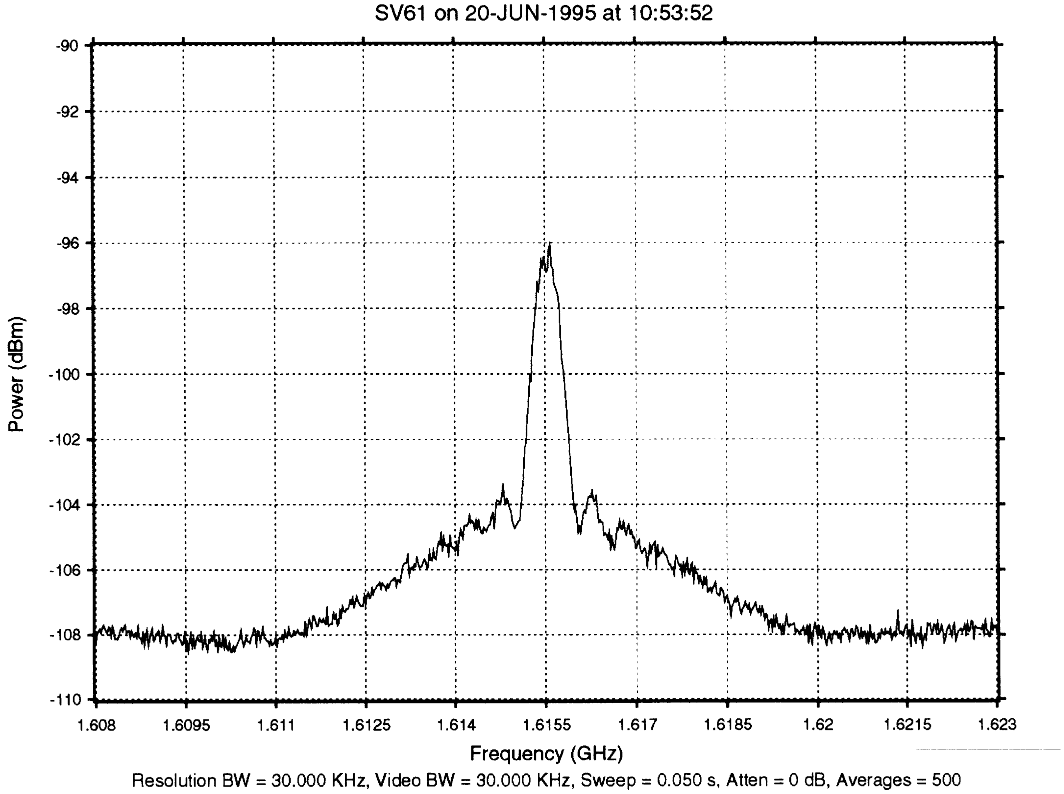


Figure A-2. GLONASS L1 C/A and P(Y) Code Spectrum

The data in each subframe is divided into two sections; the first containing the coordinates and clock parameters of the transmitting satellite and the second almanac parameters for all other satellites currently in the system. Various flags occur in the message relating to validity of specific data, status and health of particular satellites. Several data message have not been published or are only partially understood, for example, the luni-solar correction term in the almanacs.

GLONASS ephemerides are similar to the format used by Cicada satellites. Both systems encode the satellite's instantaneous position and velocity at fixed time intervals in an earth-centred earth-fixed (ECEF) rectangular coordinate system. Positions and velocities at intermediate times are calculated by the user using interpolation. In addition to positional data at reference times, GLONASS also transmits in the ephemeris two parameters relating to the on board-clocks. The first is a time correction for the instantaneous time difference between space vehicle time and GLONASS system time. The second parameter a frequency correction gives the rate of change of space vehicle time offset. An age-of-ephemeris-data (AODE) parameter is included to allow the user to calculate the satellites time and frequency offset at the time the transmission occurred.

There is greater similarity between Navstar and GLONASS in the transmission of almanacs. Both systems transmit the basic elements of a osculating Kepler ellipse, as illustrated in Table A-3. In terms of using almanacs to predict satellite position from the reduced Kepler orbit, the two sets of data are similar. Where differences occur (parameter 8), the terms are seen to be

Table A-3. Almanacs

Parameter	NAVSTAR	GLONASS
1	week of validity	day of validity
2	identifier	channel number
3	eccentricity	-
4	inclination	-
5	time of almanac	equator crossing time
6	health	validity of almanac
7	right ascension ascending node (RAAN)	equator crossing longitude
8	rate of change of RAAN	-
9	root of semi-major axis	orbital period
10	argument of perigee	argument of perigee
11	mean anomaly	-
12	-	luni-solar term
13	time offset	time offset
14	frequency offset	-

equivalent. The primary purpose of almanac data is to allow the user to predict in approximate terms the visible satellites and their geometry.

Almanac data provides a position of each satellite to within 100-200 m similar to GPS almanacs. However, the inclusion in the GLONASS almanac of a luni-solar correction term implies a position error perhaps an order of magnitude better than a Navstar almanac over an extended time period. The luni-solar term remains substantially constant for satellites with the same Right Ascension. Although the almanac is valid for several days they are usually but not always changed every day in GLONASS at local midnight.

It is interesting to observe that the GLONASS almanacs differ from the earlier Cicada almanacs in one major respect. The earlier almanacs were based on an equitial-tial Kepler set where eccentricity and argument of the perigee are transmitted as h = e x sinw and 1 = e x cosw. The equinoctial set of elements is suitable for orbits with small eccentricity since it leads to equations with no singularities when e tends to zero.

A.14 NAVIGATION REFERENCE FRAME

GLONASS employs a geocentric cartesian system designated SGS85. The difference from the GPS WGS84 frame is not large. Misra, Ref 8 reported differences of less than 20 m RMS. The two coordinate frames may be brought together by a small rotation 0.6" (3.10^{-6} rad) of the z-axis and a 4 m displacement of the origin along the z-axis.

Recently there has been a suggestion that the GLONASS coordinate frame has been updated to a SGS90 designation.

A.15 USER EQUIPMENT

A major problem with the use of GLONASS has been the lack of user equipment. Due to the initial secrecy of the system and the lack of information concerning its development few western manufactures have mature products. Receivers are made by 3S Navigation and Leeds University. By comparison with GPS equipments the costs are extremely high. A number f companies, Canadian Marconi, Trimble etc that were developing equipments in the late 1980's are apparently in abeyance. This decision was probably made at the time when a GLONASS launch had not occurred for approximately a year and the future of the system was in doubt. had not There has been some Russian equipment available vis a German sources but supplies were limited. New equipment is under development and is due to be released in late 1995.

A.16 REFERENCES

1. S Fairheller, USAF, *The Russian GLONASS System: A US AirForce /Russian Study*, US ION Sept 94

2. P Daly, *GLONASS: The USSR Navigation Equivalent,* Dept of Electrical Eng, University of Leeds. (First appeared ANP-2 version 1 Feb 1991)

3. V N Kazantsev, M F Reshetnev, A G Kozlov, V F Cheremisin *Overview and Design of the GLONASS system* NPO PM Krasnoyarsk-26

4. Russian Federation *Technical Description and Characteristics of the Global Space Navigation System* GLONASS-M, International Telecommunication Union, Radiocommunication Study Group, Nov 1994

5. G Lennon, Universtity of Leeds, The USSR's GLONASS P-code - Determination and Initial Results, ION GPS 1990.

6. J Besser, J Danaher. *The 3S Navigation R-100 Family of GPS receivers,* ION National Technical Meeting 1993.

7. Research and Production Association of Applied Mechanics, Institute of Space Device Engineering, *Global Satellite Navigation System GLONASS: Interface Control Document*, ICAO DOC. FANS/4-WP/75, May 1988.

8. P N Misra R I Abbot *SGS85 - WG84 Transformations*, Lincoln Laboratory, MIT, Lexington Mass, Manuscropta Geodaetica Spring 1994

THIS PAGE INTENTIONALLY LEFT BLANK

ANNEX B: WORLD GEODETIC SYSTEM 1984: A MODERN AND GLOBAL REFERENCE FRAME

This article has been provided by
Dr. Muneendra Kumar
who is the Defence Mapping Agency Action Officer
for the implementation of the World Geodetic System 1984.

B.1 INTRODUCTION

In this complex world where numerous Mapping, Charting, and Geodetic (MC&G), and digital products are defined in various local and/or regional geodetic datums, it becomes a straight forward requirement to simplify MC&G complexity by referencing all the products to a common reference frame globally. With this need in mind, the Defense Mapping Agency (DMA) has been actively involved since 1960 in the development of World Geodetic System (WGS). To date, four such systems, viz., WGS 60, WGS 66, WGS 72, and WGS 84, each successively more accurate, have been developed.

The latest WGS 84 represents DMA's state-of-the-art modeling of the earth from a geometric, geodetic, and gravitational standpoint using data, techniques, and technology available through early 1984.

B.2 THE REFERENCE FRAME

The origin of the WGS 84 reference frame is the earth's center of mass and the Z- and X-axes are identical to the Conventional Terrestrial System (CTS) as defined by the Bureau International de l'Heure (BIH) for the epoch 1984.0 (Figure B-1). This frame constitutes a mean or standard earth rotating at a constant rate (w) around an average astronomic pole fixed in time.

In turn, the WGS 84 reference frame is related to an Instantaneous Terrestrial System (ITS) and a Conventional Inertial System (CIS):

$$\text{WGS 84 (CTS)} = [A]\,[B]\,[C]\,[D]\ \text{CIS} \tag{1}$$

where the rotation matrices for polar motion [A],sidereal [B], notation [C], and precession [D] are from the FK 5 System referenced to Epoch J2000.0.

For practical realization, the WGS 84 reference frame or coordinate system was defined by suitable modifying the NSWC9Z-2 coordinate system of the Navy Navigation Satellite System (NNSS). This modification consisted of the removal of biases in the origin, scale, and longitude definition of the Doppler system and is defined as:

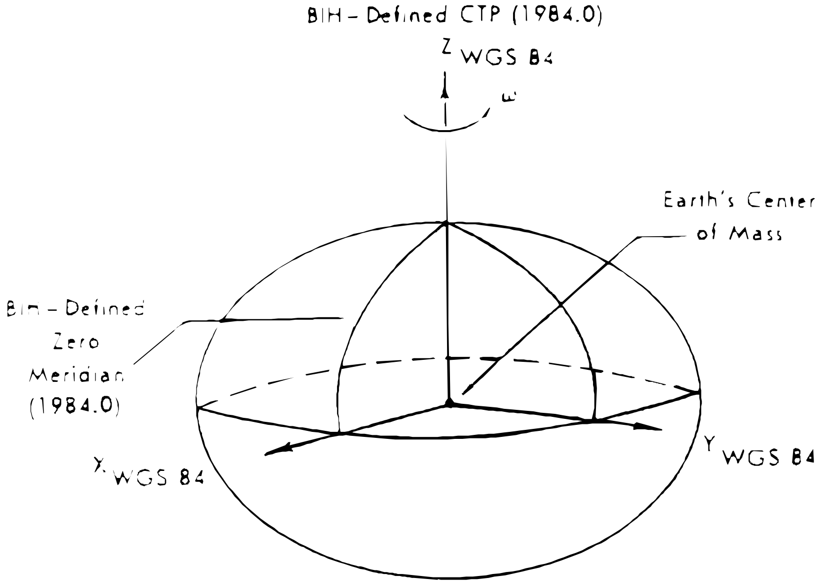


Figure B-1. World Geodetic System 1984 Reference Frame

$$Z(\text{WGS 84}) = Z(\text{NSWC 9Z-2}) + 4.5 \text{ meters} \quad (2)$$

$$S(\text{WGS 84}) = S(\text{NSWC 9Z-2}) - 0.6 \text{ ppm} \quad (3)$$

$$l(\text{WGS 84}) = l(\text{NSWC 9Z-2}) + 0.814'' \quad (4)$$

In the above relationships, Equations 2-4 refer to the Z-axis bias, scale correction, and longitudinal bias in the definition of the prime meridian, respectively, and the WGS 84, thus achieved, is coincident with the BIH-defined CTS[1].

Origin = Earth's center of mass.

Z-Axis = Parallel to the direction of the Conventional Terrestrial Pole (CTP) for polar motion, as defined by the Bureau International de L'Heure (BIH) on the basis of the coordinates adopted for the BIH stations.

X-Axis = Intersection of the WGS 84 Reference Meridian Plane and the plane of the CTP's Equator, the Reference Meridian being parallel to the Zero Meridian defined by the BIH on the basis of the coordinates adopted for the BIH stations.

Y-Axis = Completes a right-handed, ECEF orthogonal coordinate system, measured in the plane of the CTP Equator, 90 degrees East of the X-Axis.

B.3 THE DEFINING PARAMETERS AND ASSOCIATED CONSTANTS

In geodetic considerations, three different surfaces or earth figures are normally involved and used. In addition to the earth's actual physical surface, the other two include a geometric (or mathematical) reference surface, the ellipsoid, and an equipotential surface, the geoid.

In determining the WGS 84 Ellipsoid and its associated defining parameters, the WGS 84 Development Committee decided to adopt the International Union of Geodesy and Geophysics (IUGG) defined Geodetic Reference System (GRS) 1980 as its reference.

The WGS 84 Ellipsoid, as an integral component of the system for the earth's geometric figure and theoretical gravity definition, is a geocentric, equipotential, ellipsoid of revolution; Table B-1 lists the four defining parameters adopted from the GRS 80[2], except for one minor exception. The WGS 84 defines C_2 instead of J_2 of GRS 80.

Table B-1. WGS 84 Ellipsoid Four Defining Parameters

Parameters	**Notation**	**Magnitude**	**Accuracy (1s)**
Semimajor Axis	a	6378137 m	±2 m
Normalized Second Degree Zonal Harmonic Coefficient of the Gravitational Potential	$C_{2,0}$	$-484.16685 \times 10^{-6}$	$\pm 1.30 \times 10^{-9}$
Angular Velocity of the Earth	w	7292115×10^{-11} rad/s	$\pm 0.1500 \times 10^{-11}$ rad/s
The Earth's Gravitational Constant (Mass of Earth's Atmosphere Included)	GM	39860065×10^{8} m^3/s^2	$\pm 0.6 \times 10^{8}$ m^3/s^2
Parameter Values for Special Applications			
The Earth's Gravitational Constant (Mass of Earth's Atmosphere Not Included)	CM’	3986001.5×10^{8} m^3/s^2	$\pm 0.6 \times 10^{8}$ m^3/s^2
Angular Velocity of the Earth (In a Processing Reference Frame)	w^*	$(7292115.8553 \times 10^{-11} + 4.3 \times 10^{-15} T_U)$ rad/s	$\pm 0.1500 \times 10^{-11}$ rad/s
T_U = Julian Centuries From Epoch J2000.0			

Other associated constants adopted and used in WGS 84 are given in Table B-2.

Table B-2. Relevant Miscellaneous Constants and Conversion Factors

Constant	Symbol	Numerical Value
Velocity of Light (in a vacuum)	c	299792458 m/s
Dynamical Ellipticity	H	1/305.4413
Earth's Angular Velocity [for Satellite Applications; see Equation (3-14), reference 3]	w^*	(7292115.8553 x 10^{11} + 4.3 x 10^{-15} $T_{u)}$ rad/s
Universal Constant of Gravitation	G	6.673 x $10^{-11}m^3/s^2kg$
GM of the Earth's Atmosphere	GM_A	3.5 x $10^8m^3/s^2$
Earth's Gravitational Constant (excluding the Mass of the Earth's Atmosphere)	GM’	3986001.5 x $10^8m^3/s^2$
Earth's Principal	A	8.0091029 x 10^{37} kg m^2
Moments of Inertia	B	8.0092559 x 10^{37} kg m^2
Dynamic Solution	C	8.0354872 x 10^{37} kg m^2
Conversion Factors		
1 Metre	= 3.28083333333 U.S. Survey Feet	
1 Metre	= 3.28083989501 International Feet	
1 International Foot	= 0.3048 Metre (Exact)	
1 U.S. Survey Foot	= 1200/3937 Metre (Exact)	
1 U.S. Survey Foot	= 0.30480060960 Metre	
1 Nautical Mile	= 1852 Meters (Exact) = 6076.10333333 U.S. Survey Feet = 6076.11548556 International Feet	
1 Statute Mile	= 1609.344 Meters (Exact) = 5280 International Feet (Exact)	

B.4 THE GRAVITY FORMULA

In many applications, such as the computation of gravity anomalies, theoretical (or normal) gravity (g) is required as a reference value. Values of gf in the WGS 84 (for any latitude F) can be computed using the closed formula:

$$= \ {}_{e}\frac{(1 + k \sin^2\ \ )}{(1 - e^2 \sin^2\ \ )^{1/2}}$$

T_u = Julian Centuries from Epoch J2000.0

Where,

g_e = Normal gravity at the equator
= 978032.67714 mgal
k = 0.00193185138639
e^2 = 0.00669437999013.

B.5 THE EARTH GRAVITATIONAL MODEL

The Earth Gravitational Model (EGM) of the WGS 84 is a spherical harmonic expansion of the earth's gravitational potential and is defined complete through degree (n) and order (m) 180, comprising 32.755 coefficients. However, only the coefficients through n = m = 18 are unclassified[3].

Accuracy values are not available for all the WGS 84 EGM coefficients; however, an error covariance matrix is available only for coefficients through n = m = 41, which were determined from the weighted least squares solution.

B.6 THE GEOID

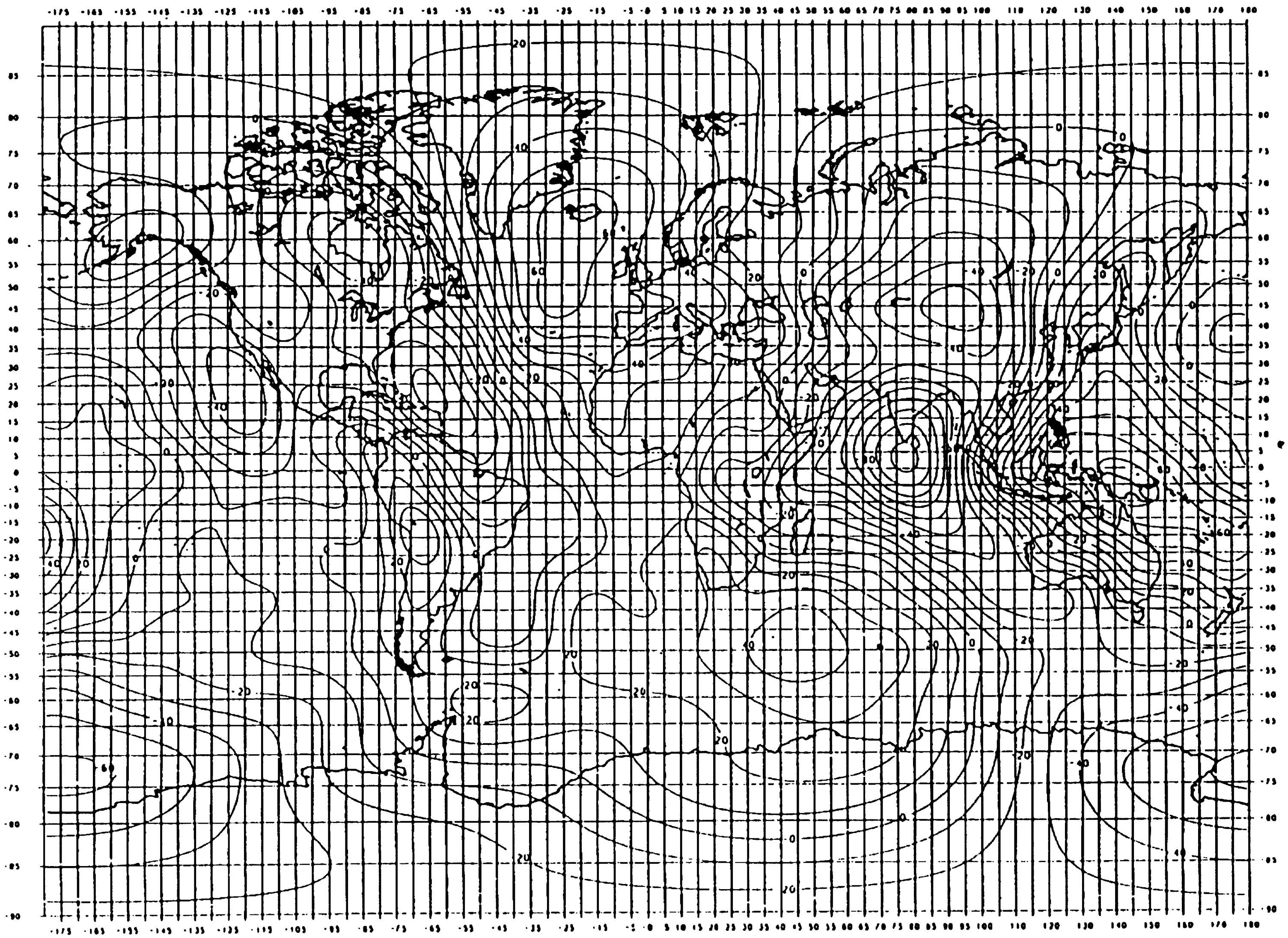
In addition to the earth's geometric surface or figure, the WGS 84 geoid, as the equipotential figure of the earth (also approximately by mean sea level over the oceans), is defined as so many meters above (+N) or below (-N) the WGS 84 ellipsoid, where "N" is known as geoidal height or undulation.

The worldwide geoidal heights were calculated using the WGS 84 EGM through n = m = 180, and they can also be depicted as a contour chart (showing deviations from the WGS 84 ellipsoid) or as a grid of desire density. Figure B-2 shows a worldwide WGS 84 geoid chart developed from a worldwide 1 degree x 1 degree grid using the unclassified EGM coefficients through n = m = 18.

The Root Mean Square (RMS) geoidal height for WGS 84, taken worldwide, is 30.5 meters and the error ranges from ±2 to ±6 meters (1s). The accuracy of the WGS 84 geoid is better than ±4 meters over approximately 93% of the globe.

B.7 RELATIONSHIP WITH LOCAL GEODETIC DATUMS

Counting islands and/or other "astro" datums, the number of local geodetic datums available for MC&G requirements and applications exceeds several hundred. If the inherent technical difficulties of dealing with these numerous local datums, each defined with its own specifications and basic limitations, are considered in daily usage, the picture is just too complex and almost chaotic.



WGS 84 Geoid (n = m = 18 Truncation) Referenced to WGS 84 Ellipsoid ($\overline{\delta C}_{4,0}$, $\delta C_{6,0}$, $\delta C_{8,0}$, and $\overline{\delta C}_{10,0} \neq 0$; Units = Meters).

Figure B-2. WGS 84 Geoid (n=m=18 Truncation)

Under this bleak scenario, one of the principal purposes of a WGS is to provide the means whereby these numerous local geodetic datums can be referenced to a common system (or to each other indirectly through extrapolation) and then, WGS can facilitate simplification of the global MC&G problem.

To achieve the referencing of a local datum to WGS 84, one major requirement is to have well-distributed control points common to both the systems. DMA maintains a world wide database of NNSS Doppler station. A search of this database produced 1591 good quality Doppler-stations, which also had coordinates defined in the local datum of the area.

These 1591 Doppler stations cover 83 local geodetic datums spread out over all the six continents-[3]. From a high of 405 Doppler stations common with the North American Datum-(NAD) 1927 in the contiguous U.S., there are 29 datums with only one common station. This limitation of not having any check station thus affects about 35% (29 of 83) of the datums.

As the local geodetic datums are generally defined only horizontally and provide mean sea level (MSL) heights from separately defined vertical datums, the geodetic heights in the local datum (H_{LD}), required to compute datum transformation parameters, were generated using the following equation:

$$H_{LD} \text{ » } h_{msl} + N_{LD} \tag{6}$$

In the above equation, the local datum geoidal heights (N_{LD}) were obtained by appropriate transformation from the WGS 84 geoidal heights. These local geoids are absolute (contrary to the relative astro-geodetic that are available for a few of the local datums) and consistent in definition with each other and also with the WGS 84 geoid worldwide.

Table B-3 provides a sample listing of the transformation parameters between the 83 local datums and the WGS 84; a full listing is available elsewhere.[4]

In addition to the 83 local datums related to the WGS 84 through Doppler ties to the local control, transformation parameters (based on non-Doppler information) are also available for seven additional local datums.[4]

B.8 ACCURACY

The accuracy of the WGS 84 coordinates of a site significantly influenced by the method used to determine the coordinates. Table B-4 lists the four methods generally available to establish the coordinate of a WGS 84 site and the associated accuracies achievable through each of the methods.

From Table B-4, it is noticed that Method 1 (where a WGS 84 site is established through direct satellite observational data) gives the most accurate positional fix of 1-2 meters. Method 4 (the least accurate) is entirely dependent on the local/regional distortion of the local geodetic datum.

Table B-3. Transformation Parameters Local Geodetic Systems to WGS 84
(For Complete Table - See Reference 4.)

Local Geodetic Systems*	**Reference Ellipsoids and Parameter Differences****			**Number of Doppler Stations Used to Determine Transformation Parameters**	**Transformation Parameters****		
	Name	**Da(m)**	**Df x 10^4**		**DX(m)**	**DY(m)**	**DZ(m)**
PROVISIONAL SOUTH AMERICAN 1956 Mean Value (Bolivia, Chile, Colombia, Ecuador, Guyana, Peru, and Venezuela)	International	-251	-0.14192702	63	-288	175	-376
PUERTO RICO Puerto Rico and Virgin Islands	Clarke 1866	-69.4	-0.3726439	11	11	72	-101
QATAR NATIONAL Qatar	International	-251	-0.14192702	3	-12	-283	22
QORNOQ South Greenland	International	-251	-0.14192702	2	164	138	189
REUNION Mascarene Island	International	-251	-0.14192702	1	94	-948	-1262
ROME 1940 Sardinia Island	International	-251	-0.14192702	1	-255	-65	9

*Geoid heights computer using spherical harmonic expansion and WGS 894 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic systems

**WGS 84 minus local geodetic system

Table B-4. Methods of Determining and Accuracy of WGS 84 Coordinates

Method of Determining WGS 84 Coordinates	**Achievable Accuracies (1s)**
1. Directly Established in WGS 84 Coordinate System via a Satellite Point Positioning Solution	F and ± 1 m H ± 1 to 2m
2. By Transformation from Doppler (NSWC 9Z-2) Coordinates by Bias Removal	F and ± 2 m H ± 2 to 3m
3. By Transformation of WGS 72 Coordinates: (a) At Doppler Sites (b) At non-Doppler Sites where WGS 72 coordinates were Obtained Indirectly from Local Datums	Same as 2., Above Dependent on the Originating Local Datum Coordinates and Transformation Errors*
4. By Transformation of Local Datum Coordinates	Same as 3.(b) Above
*See DMA TR 8350.2-A, 1 December 1987	

B.9 SUMMARY

WGS 84 is a state-of-the-art global geodetic reference system based on the use of data, techniques, and technology available within DMA through early 1984 and replaces its predecessor WGS 72. The WGS 84 reference frame, EGM, geoid, and datum transformation parameters (with local datums) are more accurate and relate more datums (83 compared to 27 for WGS 72).

These improvements can be translated into more accurate maps and charts, geodetic positioning, geoidal heights, improved satellite orbits, and the capability to relate more local datums worldwide to a unified system.

B.10 REFERENCES

1. B.I.H., "Bureau International de l'Heure Annual Report for 1984, "Paris, France, 1984.

2. Moritz, H., "Geodetic Reference System 1980," Bulletin Geodesique, 54(3):00-00, 1980.

3. Department of Defense World Geodetic System 1984, Its Definition and Relation-ships with Local Geodetic Systems; DMA TR 8350.2 Washington, DC 30 September 1987.

4. Supplement to Department of Defense World Geodetic System 1984 Technical Report; Part II-Parameters, Formulas, and Graphic for Practical Application of WGS 84; DMA TR 8350.2-B, Washington, DC 1 December 1987.

ANNEX C: BBS INFORMATION

C.1 INTRODUCTION

There are several organizations which provide computer bulletin board services for GPS and/or GLONASS users. Information available include constellation status, scheduled outages, almanacs, and other GPS related data.

The following section contains a list of BBSs listed alphabetically by country. Within each country listing, military and official services are listed first.

C.2 BBS LISTING

AUSTRALIA

AUSLIC Geodesy Electronic BBS

This bulletin board is operated by the Australian Surveying and Land Information Group of the Australian government, Canberra, ACT. It offers GPS information including recent and historical constellation status, almanac data, availability of differential GPS services and downloadable files. It also includes related geodetic information, such as solar/ionospheric data, datum transformations, and availability of coordinate and geoid/ellipsoid separations for Australia.

Dial in:	300-600 baud +61 (6) 201 4375 or +61 (6) 201 4378
Connect parameters:	N-8-1
For further information:	Jim Steed +61 (6) 201 4347 FAX +61 (6) 201 4366

CANADA

Canadian Space Geodesy Forum

This bulletin board is maintained by the University of New Brunswick. It offers daily GPS constellation status reports and ionospheric disturbance warnings. Access to e-mail is necessary to subscribe.

To subscribe:	Send the one-line message

[sub CANSPACE your_name]
to listserv @UNB.CA

For further information: Terry Arsenault (506) 453-4698
FAX (506) 453-4943
e-mail (se@unb.ca)

DENMARK

Electronic BBS

This bulletin board is operated by the Kort-og Matrikelstyrelsen, Copenhagen. GPS status advisory notices, broadcast almanacs, historical data and other information is available.

Dial in: Up to 9600 baud and MNP 10
+45 31 85 3541

Connect parameters: N-8-1

For further information: Soren Ellegaard
Kort-og Matrikelstyrelsen
Rentemestervej 8, D-2400
København, NV, Denmark
+45 35 87 5050
FAX +45 35 87 5052

FRANCE

French MOD GPS Service

The French Ministry of Defense GPS Service has two main components: a BBS and a Minitel access. It offers broadcast almanac data, ephemeris data and GPS status advisory notices information in the SEM format. It also offers weekly GPS constellation status synthesis, pseudo-ranges, precise ephemeris, integrity information and a prediction software.

Dial in: 300-14,400 baud
+33 1 48 58 37 55

Connect parameters: N-8-1

Minitel Access: 3614 GPSINF

For further information: SYSOP (Christophe Picco)
+33 1 48 58 22 22
FAX +33 1 48 58 88 78
e-mail (fdc@dialup.francenet.fr)

GERMANY

FAFGO GIBSBw

The Federal Armed Forces Geographic Office (FAFGO) is operating the GPS Information and Observation Center (GIBSBw) for use by the German Armed Forces. Topical and after the fact GPS signal status and positioning quality analysis is provided together with additional GPS-related information.

Dial in: password and user ID on request

For further information: GIBSBw
Amt für Militärisches Geowesen
Frauenberger Str. 250
53879 Euskirchen
+49 2251 7092218
FAX +49 2251 3092311

Electronic BBS

The Institute for Applied Geodesy, Frankfurt, operates this bulletin board. GPS status advisory notices, broadcast almanacs, historical data, geoid model data, real time integrity, datum transformations, availability of differential GPS services, and coverage of reference stations are available.

Dial in: Modem 1: +49 341 56 34 387
Modem 2: +49 341 56 34 388
Internet: 193.174.165.130 (no5.leipzig.ifag.de)
e-mail: gibs@leipzig.ifag.de

For further information: Georg Weber
Institute für Angewandte Geodäsie
Richard Strauss Allee 11
D-6000 Frankfurt/M70
Germany
+49 341 56 34 380
FAX +49 696 33 3425

NETHERLANDS

Electronic BBS

This bulletin board is operated by the survey department of Rijkswaterstaat, the Dutch Ministry of Transport and Public Works. It offers GPS status advisory notices, broadcast almanacs, historical data, receiver concepts and features, equipment prices and options. GPS policy statements and other information is available upon request.

Dial in:	Password and user ID on request (FAX)
For further information:	+31 (15) 691400 FAX +31 (15) 618962

UNITED KINGDOM

DRA Farnborough

This bulletin board is sponsored by MOD(E) SES 12. It offers almanacs, ephemeris and system status messages.

Dial in:	300-2400 baud +44 1252 394843
Connect Parameters:	N-8-1
For further information:	Peter Briggs +44 1252 393086

UNITED STATES

Navigation Information Center (formerly GPSIC)

The U.S. Coast Guard sponsors this bulletin board, formerly called the GPS Information Center. It offers constellation status, scheduled outages, almanac data, electronic mail, downloadable files, user advisories, and DGPS.

Dial in:	300 - 14,400 baud (703) 313-5910
Connect Parameters:	N-8-1
For further information:	(703) 313-5900 FAX (703) 3131-5920

Holloman GPS BBS (formerly Yuma BBS)

The U.S. Air Force at Holloman Air Force Base, New Mexico sponsors this bulletin board, formerly originating from the military test range at Yuma, Arizona. It offers constellation status, almanac data, electronic mail, downloadable files, and user advisories.

Dial in:	(505) 679-1525 DSN (autovon) 349-1525
Connect Parameters:	Uses "smart" modem and will automatically adjust for protocols.
For further information:	Colin Broughton (505) 679-1784 DSN (autovon) 349-1784

U.S. Army Electronic Proving Ground

The U.S. Army Electronic Proving Ground operates this bulletin board. It offers GPS status advisory notices, almanac and ephemeris data, custom satellite visibility data, electronic mail, and downloadable files.

Dial in:	300-2400 baud (602) 538-3818 DSN (autovon) 879-3818 9600 baud (602) 538-3856 DSN (autovon) 821-8087
Connect parameters:	Uses "smart" modem and will automatically adjust for protocols (default settings are N-8-1)
For further information:	Jack Underwood (602) 533-8087 DSN (autovon) 821-8087

ARINC BBS

This bulletin board is maintained by ARINC Incorporated in San Diego, CA. It offers broadcast and theoretical almanac data and GPS status advisory data information in the SEM format.

Dial in: 300-1200 baud
(619) 222-8637

Connect Parameters: N-8-1

For further information: Hana Maquet
(619) 222-7447
FAX (619) 225-1750

Scripps Orbit and Permanent Array Center (SOPAC)

This bulletin board is maintained by Scripps Institution of Oceanography, University of California, San Diego, which is a nonprofit educational institution. Precise GPS orbits are available in National Geodetic Survey format (sp1 and sp3) with a one week delay based on tracking data collected by the International GPS Geodynamics Service (IGS). There is a small fee for access to data.

Dial in: 1200-14,400 baud (619) 587-2563

Connect parameters: N-8-1

For further information: Order information is available on line or by contacting:

SOPAC
Scripps Institution of Oceanography
UCSD, IGPP 0255
9500 Gilman Dr
La Jolla, CA 92093-0225, USA
(619) 534-0229 or 534-7692
FAX (619) 534-5332
e-mail (smarquez@ucsd.edu)

IGS

The International GPS Service for Geodynamics is a service established by the International Association of Geodesy (IAG). IGS is based on about 50 globally distributed permanent GPS tracking sites and routinely provides high quality orbits for all GPS satellites, Earth rotation parameters, contributions to the determination of the tracking site coordinates in the International Terrestrial Reference Frame (ITRF), and phase and pseudorange observations in daily RINEX files for each IGS tracking site.

For further information:

Gerhard Beutler, Chairman
Ruth Neilan
Central Bureau (U.S.)
(818) 354-8330
FAX (818) 393-6686
e-mail: igscb@igscb.jps.nasa.gov

Like any other types of electromagnetic waves, GPS satellite broadcasting signals are also subject to reflection and diffraction. GPS multipath is the antenna reception of signals not directly from satellites but rather bounced off or diffracted from local objects. Since the multipath takes a longer path than the direct signal, it results in an error in pseudorange measurements and thus affects the positioning accuracy.

If the path length of the indirect signal is more than a chip length longer than the direct signal, the code correlator will not be able to correlate on the indirect signal. This is the reason why the multipath code tracking error rarely exceeds one half of the correlator chip length, which is 150 m for the conventional C/A-code correlator. For stationary or slowly moving users, the multipath error is on the order of a few meters or so for a period from a few minutes to an hour. The impact of multipath to high dynamic vehicles is even less. The multipath caused by man-made objects such as towers or electrical poles does not usually last long. However, the multipath over a vast calm water surface may continue for a while because the water surface acts like a perfect mirror.

The effect of multipath to carrier phase measurements is less severe, typically less than a quarter of the wavelength of the carrier. For L1, it is approximately 5 cm.

In general, the C/A-code is more susceptible to the multipath problem than the P(Y)-code due to the relatively narrower bandwidth, that is 2 MHz for the C/A-code versus 20 MHz for the P(Y)-code. With recent advances in narrow correlation technology, the C/A-code multipath susceptibility can match the conventional P(Y)-code performance. The same technology can also be applied to the P(Y)-code to enhance its multipath susceptibility by increasing the bandwidth from 20 MHz to 80 MHz with 0.2 chip spacing.

Since multipath is not easily predictable and not spatially correlated between two antennas except for a very short baseline, it causes a major problem for differential operation. Therefore it is important to understand the nature of multipath and hopefully eliminate its impact to GPS receiver performance.

How to Identify Multipath:

For a stationary antenna, such as the one used in a ground reference station for differential GPS operation, the multipath can be identified by monitoring the GPS signal with a second antenna separated by sufficient distance so that the multipath observed in one antenna will not be seen in the other. A significant difference in pseudorange measurements between two antennas, after proper compensation for their locations, is a strong indication of multipath. The observed discrepancies should repeat after 23 hours and 56 minutes due to the GPS constellation periodicity, providing further proof of the existence of multipath. To illustrate the repeatability of this phenomenon, Figure E-1 shows the multipath induced north position error over four consecutive days in San Diego, CA. As shown, the multipath error occurs near the same time of the day except that it advances 4 minute every day.

For a moving vehicle, the multipath can theoretically be isolated by comparing the code-tracking pseudorange measurements and the carrier tracking integrated Doppler measurements. Because the integrated Doppler multipath is only on the order of a few centimeters, the differences between the two are primarily due to the multipath in the pseudorange measurements. In order to make this technique work, the mean value of differences over a fixed period of time has to be removed in order to eliminate integer ambiguity in the integrated Doppler measurements. In an environment free of multipath, differences after removal of the mean are primarily due to receiver noise which should be less than a meter. Anything larger is an indication of possible multipath.

Another technique to identify multipath is to examine the carrier signal-to-noise ratio. When multipath occurs, the coherency of the composite signal (direct plus reflected) makes the magnitude oscillate with time depending upon the relative phase. There fore, another indication of multipath is that the carrier signal-to-noise ratio appears to vary periodically.

Since the multipath is highly geometry-dependent, when it appears, it only affects one or two satellites. For differential GPS operation, it is possible to use RAIM based algorithms to identify the existence of multipath of a specific satellite and then exclude the erroneous measurement from the position computation. There are two important factors that are critical to the success of this technique. One is that six or more satellites are needed to exclude the measurement with multipath using a RAIM based algorithm. The other is that the receiver must operate in differential mode so that the multipath, instead of SA, becomes the dominant error source.

How to Reduce Multipath:

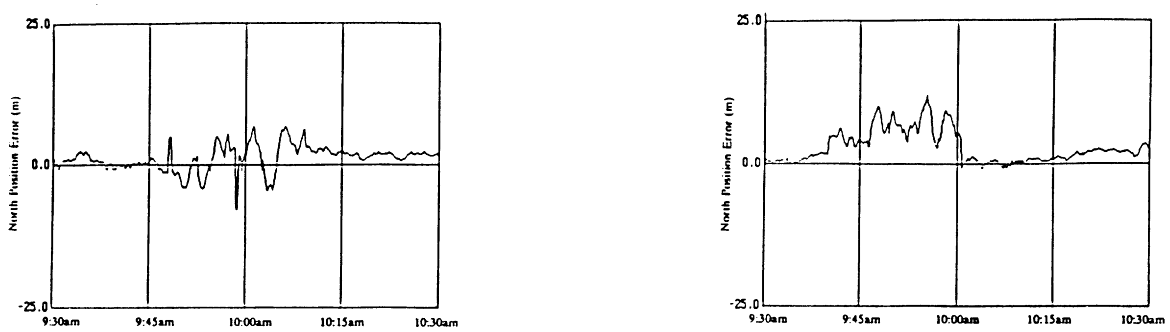
The most straightforward method to reduce multipath is to move the antenna to a multipath-free location. This is usually done by placing the antenna as low as possible and away from huge buildings. Sometimes, this is not possible due to physical restrictions. Another approach is to increase the masking angle as long as enough high elevation satellites are in view. This is because multipath often appears in the low elevation satellites for two reasons: (1) direct signal strength is weaker for low elevation satellites and (2) the increase in propagation path is smaller. Other more advanced candidate solutions to reduce multipath are discussed in the following:

1. An effective approach is to monitor the pseudorange measurements using a receiver autonomous integrity monitoring (RAIM) algorithm or carrier phase integrated Doppler. When a pseudorange measurement is suspected to be contaminated with multipath, either significantly reduce the weight or remove it completely from the position computation.

2. Because most of the reflected signal comes from below the Earth's surface, another effective approach to reduce the impact of this kind of multipath is to place the antenna directly on a large ground plane in order to shape the antenna pattern, so that is has no sidelobe under the horizon. If a large ground plane is not practical, another method is to use a choke ring, which is much smaller in size and works equally well. The choke ring consists of

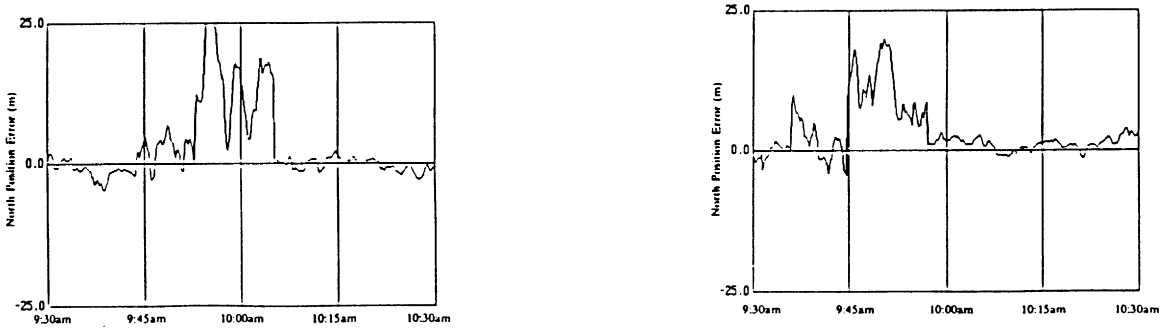
several rings with their diameters tuned to the GPS frequencies. When the reflected signal enters the antenna via edge diffraction, it will be "choked" in these rings, thus attenuating the multipath. For example, as shown in Figure D-1, the results on June 14 and 16 were obtained with an antenna mounted on a choke ring while on June 15 and 17 without a choke ring. As can be seen, the choke ring attenuated the multipath error by nearly 50%.

3. A new technique to reduce the multipath is to narrow the receiver's early-late correlator spacing in the implementation of delay lock loops, especially in C/A-code tracking applications. It was reported in the Journal of the Institute of Navigation, "Theory and Performance of Narrow Correlator Spacing in a GPS-Receiver", that 3 to 4 times improvement is achievable. Further research is-still needed to explore the full benefits of this technique.



(a) June 14, 1993

(c) June 16, 1993



(b) June 15, 1993

(d) June 17, 1993

Figure D-1. Multipath Induced North Position Error

THIS PAGE INTENTIONALLY LEFT BLANK

ANNEX E: DOCUMENTATION

E.1 INTRODUCTION

This annex lists documents that may be useful for those wishing to study GPS UE in more detail. The categories of documents are as follows:

a. Interface Control Documents (ICDs)
b. Other Documents

It should be noted that the below listed documents may not be releasable to all nations and/or agencies. Requests for these documents should be placed via diplomatic channels.

E.2 ICDs

ICD-GPS-200PR	NAVSTAR GPS Space Segment/Navigation User Interfaces Public Release

E.3 OTHER DOCUMENTATION

E.3.1 JPO Documents

YEE-82-009D	Users Overview, March 1991

E.3.2 ION Documents

"Papers Published in Journal of Navigation" Volume I, II, and III, IV

Available from:

The Institute of Navigation
Suite 832
815 Fifteenth Street N.W.
Washington DC 20005
U.S.A.

E.3.3 RTCM Document

"Recommendations of Special Committee 104 Differential NAVSTAR GPS Service"

Available from:

Radio Technical Commission for Maritime Services
Suite 300
615 Fifteenth Street N.W.
Washington DC 20005
U.S.A.

E.3.4 RTCA Document

DO-208	"Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning Service (GPS), July 1991
DO-217	"Minimum Aviation System Performance Standards DGNSS Instrument Approach System: Special Category I (SCAT-I), August, 1993

Available from:

RTCA
1140 Connecticut Ave, N.W., Suite 1020
Washington, D.C. 20036 U.S.A
(202) 833-9339
FAX (202) 833-9434

E.3.5 DoT Documents

Federal Radio Navigation Plan (FRP)

Available from:

The National Technical Information Service
Springfield, VA 22161
Document DOT-VNTSC-RSPA-92-2/DOD-4650.5

FAA-EM-82-15 Evaluation of Various Navigation System Concepts, March 1982

E.3.6 Miscellaneous

"The Global Positioning System (GPS) SPS Performance Specification", November 5, 1993.

"National Marine Electronics Association NMEA 0183 Standard for Interfacing Marine Electronic Devices", January 1, 1992

Available from:

Robert Sassaman
NMEA Executive Director
P.O. Box 50040
Mobile, AL 36605
U.S.A.
(205) 473-1791
FAX (205) 473-1669

"Technical Characteristics of the Navstar GPS", June 1991.

ANNEX F: ABBREVIATIONS AND ACRONYMS

AAIM	Aircraft Autonomous Integrity Monitoring
A/D	Analog-to-Digital
A-J	Anti-Jamming
A-S	Anti-Spoofing
ACU	Antenna Control Unit
ADOP	Along-track Dilution of Precision
AE	Antenna Electronics
AEEC	Airlines Electronic Engineering Committee
AEU	Antenna Electronic Unit
AFB	Air Force Base
AFMC	Air Force Materiel Command
AFSCN	Air Force Satellite Control Network
AFSPC	Air Force Space Command
AGPS	Augmented GPS
AHRS	Attitude and Heading Reference System
AIM	Autonomous Integrity Monitoring
AIMS	Air Traffic Control Radar Beacon System Identification of Friend or Foe
AOC	Auxiliary Output Chip
AOED	Age-of-Ephemeris-Data
ATR	Air Transport Racking
AUTONAV	Autonomously Navigate
BBC	Backup Bus Controller
BC	Bus Controller
BCD	Binary Code Decimal
BIH	Bureau International de L'Heure
BIM	Broadcast Integrity Message
BIPM	Bureau International des Poids et Mesures
BIT	Built-In-Test
BPS	Bits per second
BPSK	Bi Phase Shift Keyed
C/N	Carrier to Noise Ratio
C/A	Coarse Acquisition-code
CAA	Civil Aviation Authorities
CADC	Central Air Data Computer
CAS	Cost Accounting Standard
CCAFS	Cape Canaveral Air Force Station
CDNU	Control Display Navigation Unit
CDU	Control Display Unit
CEP	Circular Error Probable (50%)
CHN	Channel
CIS	Conventional Inertial System

CLRP	Continuing Low-Rate Production
COMSEC	Communications Security
CRPA	Controlled Radiation Pattern Antenna
CTP	Conventional Terrestrial Pole
CTS	Conventional Terrestrial System
dB	Decibel
dBHz	Decibels with respect to one Hertz
dBic	Decibel with respect to isentropic circularly polarized radiation
dBW	Decibels with respect to one Watt
DGPS	Differential GPS
DLM	Data Loader Module
DLR	Data Loader Receptacle
DLS	Data Loader System
DMA	Defense Mapping Agency
DoD	Department of Defense
DOP	Dilution of Precision
DoT	Department of Transportation
drms	Distance Root-Mean-Square
DRNS	Doppler Radar Navigation System
DSP	Digital Signal Processor
DT&E	Development Test and Evaluation
ECEF	Earth-Centered-Earth-Fixed
EDM	Electronic Business Measurement
EDOP	East Dilution of Precision
EFIS	Electronic Flight Instrument Systems
EGM	Earth Gravitational Model
EGR	Embedded GPS Receiver
EMI	Electro-Magnetic Interference
EMCON	Emission Control
EMP	Electro-Magnetic Pulse
ESGN	Electrically Suspended Gyro Navigator
EUROCAE	European Organization for Civil Aviation Electronics
EUROCONTROL	European Organization for the Safety of Air Navigation
FAA	Federal Aviation Administration
FAFB	Falcon Air Force Base
FDE	Fault Detection and Exclusion
FOC	Full Operational Capability
FOM	Figure of Merit
FOUO	For Official Use Only
FRP	Federal Radionavigation Plan
FRPA	Fixed Radiation Pattern Antenna
GA	Ground Antennas
GDOP	Geometric Dilution of Precision

GLONASS	Global Orbiting Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRAM	GPS Receiver Applications Module
GUV	Group Unit Variable
HAE	Host Application Equipment
HD	High-Dynamic
HDOP	Horizontal Dilution of Precision
HMI	Hazardously Misleading Information
HOW	Handover Word
HQ	Headquarters
HR	Hour
HSI	Horizontal Situation Indicator
HV	Host Vehicle
Hz	Hertz
IAW	In Accordance With
IBM	International Business Machines
ICAO	International Civil Aviation Organization
ICAR	International Agreement Competitive Restriction
ICD	Interface Control Document
IF	Intermediate Frequency
IFR	Instrument Flight Rules
ILS	Instrument Landing System
INS	Inertial Navigation System
IOC	Initial Operational Capability
ION	Institute of Navigation
IP	Instrumentation Port
IPT	Integrated Product Team
IRS	Inertial Reference System
ITS	Intermediate Test Set
ITS	Instantaneous Terrestrial System
IUGG	International Union of Geodesy and Geophysics
IWSM	Integrated Weapon System Management
J/S	Jamming-to-Signal
JPO	Joint Program Office
KDOP	Weighted Variation of Dilution of Precision
Kg	Kilograms
KIR	Keyed Information Receivers
km	Kilometers

L1	Link 1
L2	Link 2
LAAFB	Los Angeles Air Force Base
LADGPS	Local Area Differential GPS
LD	Low-Dynamic
LNA	Low Noise Amplifier
LO	Local Oscillator
LRIP	Low Rate Initial Production
LRU	Line Replaceable Unit
LV	Launch Vehicle
m	Meters
MAGR	Miniaturized Airborne GPS Receiver
MAP	Military Assistance Program
MCM	Multi-Chip Module
MCS	Master Control Station
MDL	Mission Data Loader
MHz	Megahertz
MIL-STD	Military-Standard
MILDEP	Military Department
min	Minute
mm	Millimeters
MMD	Mean Mission Duration
MoD	Ministry of Defense
MOU	Memorandum of Understanding
ms	Millisecond
MS	Monitor Stations
MSL	Mean-Sea-Level
MTBF	Mean Time Between Failure
MUX	Multiplex
NAD	North American Datum
NAS	National Air Space
NATO	North Atlantic Treaty Organization
NAV-MSG	Navigation-Message
NDI	Non-Developmental Item
NDOP	North Dilution of Precision
NMEA	National Marine Electronics Association
NNSS	Navy Navigation Satellite System
NPE	Normalized Position Error
NRL	Naval Research Laboratory
ns	Nanosecond
NSA	National Security Agency
NTE	Not-to-Exceed
NTS-1	Navigation Technology Satellite-1
NTS-2	Navigation Technology Satellite-2

OASD	Office of the Assistant Secretary of Defense
OBS	Omni Bearing Select
OCS	Operational Control System
OFP	Operational Flight Program
OR	Operational Release
OT&E	Operational Test and Evaluation
OTHT	Over the Horizon Targeting
P-code	Precision Code
PAFB	Patterson Air Force Base
PC	Personal Computer
PCS	Prelaunch Compatibility Station
PDOP	Position Dilution of Precision
PLGR	Precision Lightweight GPS Receiver
PM	Phase Modulate
PMD	Program Management Directive
PMR	Program Management Reviews
POS/NAV	Positioning and Navigation
PPM	Pulse Per Minute
PPS	Precise Positioning Service (PPS)
PPS-SM	PPS Security Module
PRN	Pseudorandom Noise
PRN#	Pseudo-random Noise Number
PSK	Phase Shift Keying
PTTI	Precise Time and Time Interval
PVA	Position, Velocity, and Acceleration
PVT	Position, Velocity, and Time
R-C	Rockwell-Collins
R&D	Research and Development
RAAN	Right Ascension of the Ascending Node
RAIM	Receiver Autonomous Integrity Monitoring
REAC	Reaction Time
RF	Radio Frequency
RFP	Request for Proposal
rms	Root Mean Square
RNP	Required Navigation Performance
ROD	Report of Discrepancy
RT	Remote Terminal
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission for Maritime Service
SA	Selective Availability
SAASM	Selective Availability/Anti-Spoofing Module
SAHRS	Standard Attitude Heading Reference System
SBB	Smart Buffer Box
SC	Special Committee

SCADC	Standard Central Air Data Computer
SDC	Signal Data Converter
SEM	Systems Effectiveness Model
SEP	Spherical Error Probable
SGR	Survey GPS Receiver
SINCGARS	Single-Channel Ground and Airborne Radio System
SINS	Shipborne Inertial Navigation System
SIS	Signal-In-Space
SLGR	Small Lightweight GPS Receiver
SM	Security Module
SMC	Space and Missile Center
SME	Significant Military Equipment
SOC 31	Space Operations Center 31
SOW	Statement of Work
SPO	System Program Office
SPS	Standard Positioning Service
SRU	Shop Replaceable Units
SSS	Satellite Signal Simulator
STANAG	Standardization Agreement
SV	Space Vehicle
SVN	Space Vehicle No.
TACAN	Tactical Air Navigation
TAI	International Atomic Time
TCO	Technical Coordination Group
TDM	Time Division Multiplexed
TDOP	Time Dilution of Precision
TFOM	Time Figure Of Merit
TGR	Timing GPS Receiver
TI	Texas Instruments
TIMATION	Time Navigation
TTFF	Time-To-First-Fix
TTSF	Time to Subsequent Fix
U.S.	United States
UE	User Equipment
UEE	UE Error
UERE	User Equivalent Range Error
UK	United Kingdom
UNE	User Navigation Error
URA	User Range Accuracy
URE	User Range Error
USA	United States of America
USAF	United States Air Force
USN	United States Navy
USSPACECOM	United States Space Command
UT	Universal Time

UTC	Universal Time Coordinated
VAFB	Vandenburg Air Force Base
VDOP	Vertical Dilution of Precision
VME	Versa Module Europa
VRF	Visual Flight Rules
VSWR	Voltage Standing Wave Ratio
WAAS	Wide-Area Augmentation System
WADGPS	Wide Area Differential Global Positioning System
WGS	World Geodetic System
WGS 84	Would Geodetic System 1984
XDOP	Cross-track Dilution of Precision
Y-Code	Encrypted P-Code
YPG	Yuma Proving Grounds
1 SOPS	First Space Operations Squadron
2 SOPS	Second Space Operations Squadron
2-D	Two-dimensional
3-D	Three-dimensional
45 SPW	Forty Fifth Space Wing
50 SPW	Fiftieth Space Wing