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Global Positioning System (GPS) Time Dissemination for Real-Time Applications

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Abstract. This paper presents an overview of the Global Positioning System (GPS) for the potential precise time and time interval user with special reference to real-time systems. An overview of GPS operation is presented and GPS error sources are described as they relate to the timing user. A review of receiver types and receiver tasks provides the basis for understanding GPS time transfer techniques. The accuracies provided by different techniques are reviewed and the special requirements for GPS time and frequency receivers as well as modern timing receiver enhancements are described. The precise time standard provided by GPS is traced through its path from global standards to the user application. GPS time dissemination failure modes that result from control problems, space craft failures, and receiver failures are outlined.

1. Introduction

The Global Positioning System (GPS) is an earth-orbiting-satellite based navigation system. GPS is an operational system, providing users worldwide with twenty-four hour a day precise position in three dimensions and precise time traceable to global time standards. GPS is operated by the United States Air Force under the direction of the Department of Defense (DoD) and was designed for, and remains under the control of, the United States military. While there are now many thousands of commercial and recreational civil users worldwide, DoD control still impacts many aspects of GPS planning, operation, and use.

Primarily designed as a land, marine, and aviation navigation system, GPS applications have expanded to include surveying, space navigation, automatic vehicle monitoring, emergency services dispatching, mapping, and geographic information system georeferencing. Because the dissemination of precise time is an integral part of GPS, a large community of precise time, time interval, and frequency standard users has come to depend on GPS as a primary source of control traceable through the United States Naval Observatory to global time and frequency standards.

2. GPS Overview

2.1 History of GPS

Developed in the 1960s, the Navy Transit satellite navigation system still provides some service as a two-dimensional (horizontal) positioning system. Good (200 meter) Transit positioning requires knowledge of the user altitude as well as a model of user dynamics during the fix, a process of integrating satellite signal Doppler shifts (the change in received signal frequency caused by the changing range) during the fly-over of the satellite. Another Navy system, based on the Timation satellites, carried stable clocks (quartz, rubidium, and cesium) over the course of the program in the 1960s and 70s and was the precursor to the precise time capabilities of GPS (Easton 1978).

GPS began in 1973 as a test program using ground-based transmitters at the U. S. Army Proving Ground at Yuma, Arizona, later augmented with early versions of GPS satellites first launched in 1978. During the 1980s, GPS, although not yet fully operational and requiring careful planning for missions during times of satellite availability, was increasingly used by both military and civilian agencies. Land, air, and sea navigation, precise positioning, carrier phase survey techniques, and precise time and frequency dissemination were all accomplished to a limited extent during the initial phases of GPS deployment (Klepczynski 1983). By 1989 ten development satellites, termed Block I satellites, had been successfully launched. By 1990, 43 laboratories requiring precise time were using GPS to synchronize their atomic clocks (Clements 1990). By 1994, 24 Block II and IIA operational GPS space vehicles (SVs) had been launched. The Block IIA SVs can store up to 14 days of uploaded data in case contact is lost with ground stations and can operate for 180 days with degraded navigation receiver performance. The next generation of space vehicles, the Block IIR SVs will incorporate changes to include the capability of maintaining precise time keeping without Control Segment uploads for periods of up to 210 days by exchanging data between GPS SVs (Rawicz, Epstein, and Rajan 1992).

In December of 1993, GPS reached Initial Operational Capability, with a minimum of 24 satellites in orbit. On July 17,1995 the Air Force announced that GPS had met all requirements for Full Operational Capability with 24 Block II SVs in orbit. With over 50 companies supplying a selection of over 275 GPS receivers to a global market, the well established user community of navigators, surveyors, geologists, geodesists, time and frequency users, and many thousands of recreational users has come to accept GPS as a viable military and civilian system.

2.2 Civil and Military GPS

While controlled and maintained by the DoD, the GPS user community has a large civil component. In the 1977 *National Plan for Navigation*, published by the U. S. Department of Transportation (DoT), the NAVSTAR GPS user community was planned to include 27,000 military receivers. While the potential for a civil-sector user base was recognized, the document did not include plans for a civil GPS service (U. S. DoT 1977 3-14; 3-15).

A decade later the *Federal Radionavigation Plan* (FRP) (U. S. DoD and DoT 1986) stated that GPS would be available to civil users, worldwide, on a continuous basis but with accuracy limited to 100 meters (95 percent).

In these radionavigation documents position accuracy is usually specified as a two standard deviation (95 percent) radial error or 2drms (2 distance root mean squared) uncertainty estimate. For GPS the 95 percent probability and 2drms accuracy are equivalent (DoD and DoT 1995, A-2).

The 1985 *Comprehensive Global Positioning System User Policy* defined both a military, encrypted, Precise Positioning Service and a “lower level of accuracy” Standard Positioning Service (U. S. DoD and DoT 1986, B-32).

- **Standard Positioning Service**
  The Standard Positioning Service (SPS) is defined in the most recent FRP as:
  the standard specified level of positioning and timing accuracy that is available, without restrictions, to any user on a continuous worldwide basis. The accuracy of this service will be established by the DOD and DOT based on U. S. security interests. SPS provides a predictable positioning accuracy of 100 meters (95 percent) horizontally and 156 meters (95 percent) vertically and time transfer accuracy to UTC within 340 nanoseconds (95 percent).

- **Precise Positioning Service**
  The FRP defines the Precise Positioning Service (PPS) as:
  the most accurate direct positioning, velocity, and timing information continuously available, worldwide, from the basic GPS. This service is limited to users specifically authorized by the U.S. P(Y)-code capable military user equipment provides a predictable positioning accuracy of at least 22 meters (95 percent) horizontally and 27.7 meters (95 percent) vertically and time transfer accuracy to UTC within 200 nanoseconds (95 percent) (DoD and DoT 1995, A-36).

By the time the 1992 FRP was published, the projected 1995 estimate of 53,000 civil users of GPS exceeded the projected number of military users estimated at 19,000 (U. S. DoD and DoT 1993, 3-41). Civil users now constitute the majority of GPS users. The 1994 FRP estimates the current total number of GPS users at over 500,000 in the United States alone (U. S. DoD and DoT 1995, 3-7).

2.3 GPS Segments

The DoD has defined three divisions of GPS: the Control, Space, and User Segments.

- **Control Segment**

The Control Segment consists of a network of global monitor stations, located at the British colony of Ascension Island in the South Atlantic Ocean; Colorado Springs, Colorado; Diego Garcia, a U. S. military base in the Indian Ocean; Hawaii; and Kwajalein Atoll in the Republic of the Marshall Islands (Figure 1). These stations track the GPS satellites as they pass over these sites twice a day. They relay satellite range and timing measurement data to the Master Control Station at Falcon Air Force base in Colorado. There, orbital and clock data are computed for all satellites. From Master Control at Falcon, or from ground antennas at Ascension Island, Diego Garcia, or Kwajalein, orbit and clock data as well as system parameters are uploaded daily to each individual space vehicle for rebroadcast in data sets nominally replaced within the SVs every hour and used by the receiver to compute position and time of signal transmission for each SV.

- **Space Segment**

The GPS satellites comprise the Space Segment. The nominal operational constellation consists of 21 satellites and three active spares, a total of 24 SVs that orbit the earth

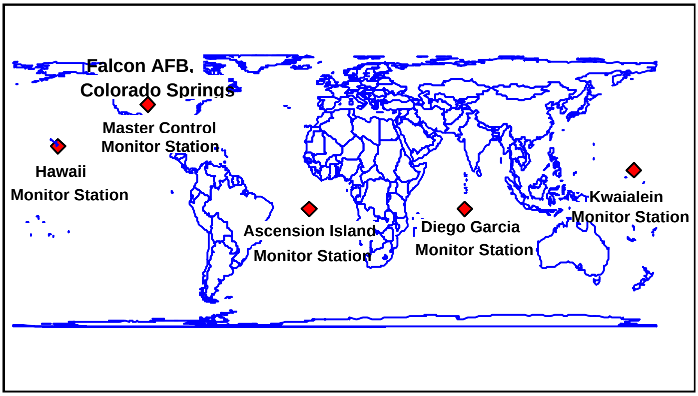


Figure 1.

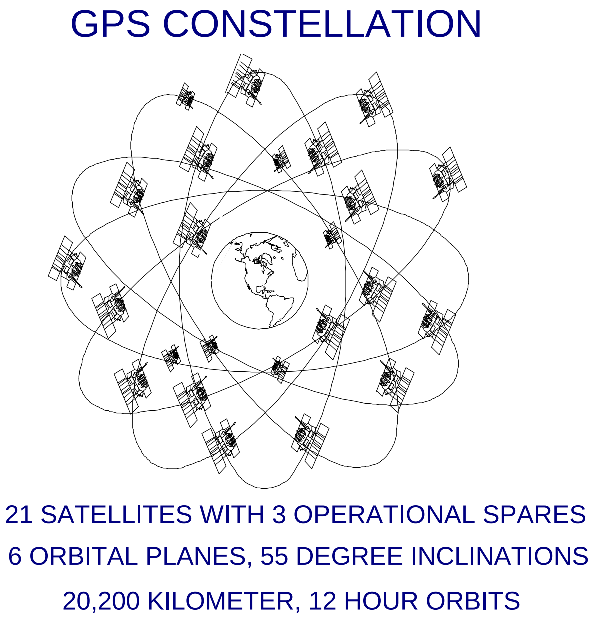


Figure 2.

at altitudes of about 20,200 kilometers above the earth (Figure 2). These satellites are arranged in six orbital planes that are inclined at a 55 degree angle, providing worldwide coverage with at least five SV visible (most of the time) from any point on the earth.

Each space vehicle broadcasts navigation signals at two microwave frequencies. These two carrier signals are phase modulated by noise-like (pseudo-random) bit streams that spread the carrier frequencies into a broader bandwidth of noise-like, spread-spectrum signals. In addition to pseudo-random noise (PRN) codes, the signals are modulated with the Navigation Message consisting of a set of orbital (ephemeris) data, satellite clock offset descriptions and other system parameters.

The L1 (1575.42 MHz) signal carries a PRN code that repeats each millisecond and that is unique for each of thirty-two SV codes. These coarse acquisition codes (C/A-codes) are broadcast at a bit (chipping) rate of 1.023 MHz and are used to identify and acquire each SV, and to align receiver timing signals with those transmitted by the SV. In addition to the C/A-code the L1 signal carries the Navigation Message code (at 50 Hz) and either the P-code or the Y-code. The P-code is a PRN code with a period of seven days that is transmitted at a chipping rate of 10.23 MHz. When encrypted prior to transmission in the satellite, the P-code becomes the Y-code and is accessible only to authorized users with Y-code Security Modules capable of handling cryptographic keys that permit decryption back into the P-code. The L2 signal, also a microwave, spread-spectrum signal (1227.6 MHz), carries only the P(Y)-code and is used for dual frequency ionospheric delay measurements.

- **User Segment**

The User Segment consists of the receivers and the agencies or individuals that deploy them. Originally conceived of as a military system, the User Segment now contains many thousands of commercial and recreational civilian users as well as military users around the world.

2.4 GPS-Time Control

GPS-Time is a continuous measurement of time from an epoch started at January 6, 1980 at midnight (0 hours 0 minutes 0 seconds) Universal Time Coordinated (UTC). GPS-Time is often stated in a number of weeks and seconds from the GPS-Time epoch. GPS-Time does not introduce leap seconds and so is ahead of UTC by an integer number of seconds (10 seconds as of 1 July 1994, 11 seconds at 1 January 1996). GPS-Time is steered by the Master Control site to be within one microsecond (less leap seconds) of UTC. The GPS Navigation Message contains parameters that allow the GPS user to compute an estimate of the current GPS-UTC sub-microsecond difference as well as the number of leap seconds introduced into UTC since the GPS epoch.

GPS-Time is derived from the GPS Composite Clock (CC), consisting of the atomic clocks at each Monitor Station and all of the GPS SV frequency standards. Each of the current (Block II) SVs contains two cesium and two rubidium clocks (Langley 1991). The U. S. Naval Observatory (USNO) monitors the GPS SV signals. The USNO tracks the GPS SVs daily, gathering timing data in 130 six-second blocks. These 780-second data sets include a complete 12.5-minute Navigation Message, containing a GPS-UTC correction and an ionospheric model. Compared to the USNO Master Clock, a set of some sixty cesium and from seven to ten hydrogen maser clocks, these GPS SV data sets are used to provide time steering data for introduction into the CC at a rate of 10^{-18} seconds per second squared.

Each GPS SV signal is transmitted under control of the atomic clocks in that SV. This space vehicle time (SV-Time) is monitored and the difference between GPS-Time and the SV-Time is uploaded into each satellite for transmission to the user receiver as the SV Clock Correction data.

2.5 The GPS Navigation Message

The GPS Navigation Message is formulated at the Master Control Station. Range measurements formed from GPS signal time of arrival measurements at the precisely known positions of the Monitor Stations are incorporated into a computer program that provides orbital data sets (ephemeris sets) that represent SV orbits over a few hours. USNO corrected GPS-Time is used to compute clock corrections for each SV. These clock correction and ephemeris data sets are uploaded from Master Control and are then rebroadcast by each SV, nominally sending a new ephemeris and clock set to the user receiver each hour.

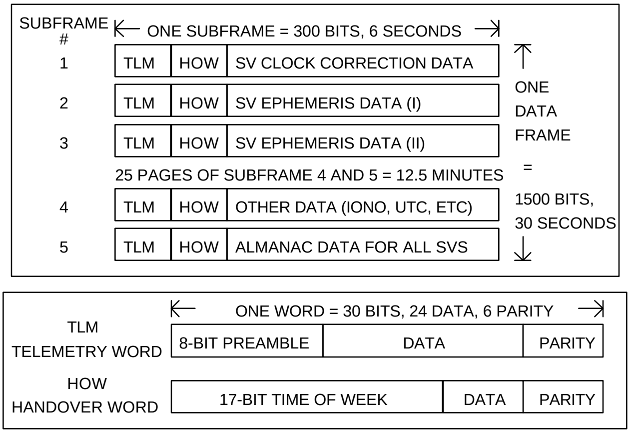
Each SV sends a continuous 50 Hz data bit stream that forms the GPS Navigation Message for that SV. The Navigation Message is sent in consecutive thirty-second data frames, consisting of five six-second subframes each made up of 300 data bits. Each data bit subframe consists of a preamble for establishing subframe synchronization and ten 30-bit words. Each subframe contains a time-of-week count in six-second increments that uniquely identifies the time of transmission for the trailing edge of the last bit in the subframe. Because the preamble (10001011) begins with a binary 1 and the last bits of all subframes are maintained as zeros, there is always a data bit transition at the moment the time-of-week is applicable.

The entire Navigation Message from an SV is a sequence of twenty-five data frames that is transmitted over a 12.5 minute period. Each data frame contains three subframes that carry the SV clock data (subframe 1) and the orbital data, or ephemeris data, for that SV (subframes 2 and 3). The additional subframes (4 and 5) are transmitted as consecutive pages (1 through 25) containing different system data including an approximate orbital data set (almanac) for each of the SVs in the system, the ionospheric model, and the UTC-GPS-Time correction parameters (Figure 3).

All of the GPS Navigation Message parameters are scaled and packed into the 30-bit data words in the subframes. Each data word consists of 24 data bits and the set of 6 parity bits representing the Hamming code for the word. Many of the GPS parameters are packed into two words, while others use just a few bits of a data word. Data parsing software in the receiver must produce parity bits to compare with the transmitted ones, fix single bit errors when detected, rectify 30-bit sequences, unpack the required data bits for each parameter and scale and perform two’s-complement operations where specified.

2.6 Basic Receiver Tasks

In the typical navigation scenario, a GPS navigation receiver acquires and tracks the signals from a set of GPS SVs. Range measurements from four SVs are used to compute a receiver clock correction and a three dimensional position fix. Each range



GPS NAVIGATION DATA FORMAT

Figure 3.

measurement is made from the alignment of SV PRN codes with replicas of these codes produced in the receiver. PRN code alignments, corrected for system offsets and transmission path delays are called "pseudo-ranges." Each pseudo-range contains the offset that results from the unaligned receiver clock. Four pseudo-ranges are sufficient to compute position in three dimensions and the receiver clock error common to each pseudo-range. When this clock bias is accounted for, the range spheres from each SV intersect at a common point providing a receiver antenna position estimate. Based on broadcast SV positions in a geocentric Cartesian coordinate system (Earth-Centered, Earth Fixed X, Y, Z) in the GPS geodetic datum (WGS-84)[1], this position can be converted to geodetic coordinates such as latitude, longitude, and height above the reference ellipsoid for any geodetic datum (see Section 5, GPS Receiver Principles, for additional details on receiver processes).

2.7 GPS Special Features

- **Selective Availability**

In the design phase of GPS, the P-code was considered the source of precise GPS position data. Early in the testing phase C/A-code receivers were able to perform almost as well as P-code receivers. While P-code receivers were able to use the L1 and L2 carrier signal delay difference to remove ionospheric errors with more success than the C/A-code only receivers using the broadcast ionospheric model, the twenty-meter P-code positioning was almost matched by the 25-30 meter C/A-code performance. To limit GPS position and velocity accuracy available to non-military users, the Department of Defense established a policy of Selective Availability (SA). SA is the introduction of time varying biases into the GPS signals to intentionally degrade performance.

SA, formally implemented in March 1990 (Georgiadou and Doucet 1990), has been in effect, except for occasional periods, since July 1991 on the Block II satellite signals. The internal SV clock signals are purposely dithered by Master Control so as to limit the position, velocity, and time accuracy available in the C/A-code signals. Because each SV signal is varied independently of the others, the position resulting from the combination of SV signals cannot be averaged over short periods of time to recover position accuracy. The SA bias for a single satellite appears to have spectral components with periods of from just a few seconds to many hours.

As the SV pseudo-ranges are each affected by SA, so are the time measurements made by a timing receiver at a fixed location. Even in a fixed and correct position, a receiver measuring GPS-Time will be in error by the amount to which the measured SV ranges vary with SA. Because SA can result in 100 meter (95 percent) horizontal positioning errors, the resulting time error can be as much as 340 nanoseconds (95 percent).

Because of the wide availability of civil C/A-code receivers at very low prices (less than $300 US), many military missions have employed civilian, C/A-code receivers, rather than the less available and more expensive military P-code receivers. During both the Gulf War and the incursion into Haiti, the DoD directed that SA be turned off, increasing the accuracy of the C/A-code receivers to their original capabilities. There are rumors that SA will soon be turned off due to public pressure from the thousands of civil users and the increasing use of GPS in projects sponsored by the Federal Aviation Administration and the United States Coast Guard. In March of 1996, The White House Office of Science and Technology Policy issued a U.S. Global Positioning System Policy directive (The White House 1996), in which DoD was instructed to “develop measures to prevent the hostile use of GPS and its augmentations to ensure that the United States retains a military advantage without unduly disrupting or degrading civilian uses.” The directive further stated that “beginning in 2000, the President will make an annual determination on continued use of GPS Selective Availability.” For now Selective Availability is active and DoD policy statements have thus far been interpreted to indicate that SA will continue at the present degradation levels, at least for the next four years..

- **Jamming Resistance**

The P-code spreads the GPS carrier signals (L1 and L2) over a 10 MHz range. This makes jamming, the intentional or unintentional disturbance of the GPS signals, difficult for a low power transmitter. To effectively jam GPS signals a transmitter must provide appreciable power over a substantial portion of the GPS spectrum, rather than in a single frequency band. While studies indicate that GPS can be jammed, the spread spectrum techniques provide a measure of protection against most hostile or inadvertent transmission in or near the GPS bandwidth.

- **Anti-Spoofing**

When the P-code is encrypted, it is called the Y-code and the Anti-Spoofing (AS) mode of GPS is on.. This encrypted code restricts access to the Precise Positioning Service. The encryption of this GPS signal is both to deny access to unauthorized users and to prevent a GPS-like transmission from capturing the tracking loops of a GPS receiver, spoofing, or fooling it into following the signal from a non-GPS source, perhaps a transmitter under control of a non-DoD agency.

3. GPS Error Sources

The GPS signals sent from the SVs are subject to a variety of error sources before they are processed into a position and time solution in the receiver. As with most systems these error sources take the form of zero-bias noise, bias errors, and blunders.

- **Selective Availability**

Selective availability is the single largest source of C/A-code error. Y-code capable GPS receivers can remove SA with knowledge of the SA algorithm. SA takes the form of a slowly varying range error for each SV. SA introduces the largest bias errors in the Standard Positioning System accounting for most of the 100 meter (95 percent) error in the SPS.

- **Clock and Ephemeris Errors**

Clock and ephemeris data sets represent the difference between the SV clock and GPS-Time and permit the estimation of SV position at the time of transmission of the tracked codes. A GPS parameter, the User Range Accuracy (URA), is a range error estimate indicative of the “maximum value anticipated during each subframe fit interval with uniform SA levels invoked” (Anon 1995, 35). The URA is transmitted as an integer power of two. Although the URA is not specified as a definite indicator of SA error magnitude, for a Block II SV affected by SA, a URA of 32 meters is common.

- **Ionospheric Delays**

A major source of bias error is the delay of the GPS carrier signals as they pass through the layer of charged ions and free electrons known as the ionosphere. Varying in density and thickness as it rises and falls (50 to 500 kilometers) due to solar pressure and geomagnetic effects, the ionosphere can delay the GPS signals by as much as 300 nanoseconds (100 meters) (Klobuchar 1982, 1). The diurnal (24-hour) changes in the ionosphere cause the largest variations in delay. At night the delay is at a minimum and the thinner and higher night-time ionosphere is more easily modeled than the less dense and thicker layer during the day. The signals from SVs at low elevation angles with respect to the local horizon experience the largest delays as the signal passes through more ionosphere than if the SV were directly overhead.

Using the P-code, or special codeless (signal-squaring) techniques, the delay through the ionosphere can be computed by a receiver capable of measuring the phase delay difference between the code carried on the L1 and L2 signals. These dual frequency methods result in a substantial reduction of the ionospheric bias, making it possible to transfer sub-nanosecond clock offset measurements over thousands of kilometers (Dunn and others 1993, 174).

For a single frequency (L1) C/A-code receiver the ionospheric delay can be estimated from the ionospheric delay model broadcast by the SVs. The Master Control station calculates the parameters for delay using a cosine model that computes delay for a given local time-of-day and the elevation angle for the path from the receiver to an SV. Some users compute an ionospheric delay estimate from their own models. Using the broadcast model under normal conditions removes about half of the error (Fees and Stephens 1987) leaving a residual error of around 60-90 nanoseconds during the day and 10 to 20 nanoseconds at night (Knight and Rhoades 1987). Signals from SVs at high elevation angles experience smaller delays, but use of the broadcast model under abnormal conditions can occasionally introduce more error than that caused by the actual delay.

- **Tropospheric Delays**

GPS signal delays through the troposphere, the layer of atmosphere usually associated with changes in weather (from ground level up to 8 to 13 kilometers), are subject to local conditions and are difficult to model. GPS does not broadcast a tropospheric correction model but several such models have been developed. Some receivers make a limited model available that computes tropospheric delay from receiver height and SV elevation angle using nominal atmospheric parameters. Because accurate tropospheric delay models (Turner and others 1986) require local pressure, temperature and humidity (PTH) data as well as receiver height and elevation angle to the SV, these models are difficult to apply in real-time situations. The errors introduced by an un-modeled troposphere may be as much as 100 nanoseconds at low elevation angles (less than 5 degrees), but are more typically in the 30 nanosecond range (Knight and Rhoades 1987). Residuals after application of a simple, no-PTH, model (Gupta 1980) are in the 10 nanosecond range.

- **Multipath**

Multipath interference, caused by local reflections of the GPS signal that mix with the desired signal, slowly introduces varying bias errors of one to two nanoseconds for navigation receivers aboard aircraft in flight. For land-based systems, local conditions and exact antenna placement can result in errors of up to 150 nanoseconds. Nominal errors for land-based receivers are in the 30 nanosecond range (Braasch 1995).

Careful attention to antenna placement, antenna design, the use of choke rings, and the use of materials that absorb GPS radio-frequency signals can mitigate much of the potential multipath interference, but these measures must be carefully designed to allow for the different multipath reflections from the constantly changing SV elevations and azimuths. In many applications it is difficult or impossible to completely eliminate multipath errors.

- **GPS Signal Noise**

Propagation of the GPS signals from the SV to the receiver introduces noise from galactic sources, ionospheric scintillations, and cross correlation from other GPS SV signals that results in small noise (zero bias) errors in the three nanosecond range.

- **Receiver Noise and Delays**

Receiver noise can introduce two to three nanoseconds of zero bias noise in the timing measurements of a GPS receiver. Delays within a receiver can be calibrated by the manufacturer, but if receiver delays change with temperature or change differently between channels of a multi-channel receiver, timing bias errors can result.

Antenna cable delays must be recomputed or calibrated if cable lengths change or cables of different materials are used. There have been reports of cable delays being both temperature and signal strength dependent (Lewandowski, Petit and Thomas 1991, 5). Manufacturers can provide cable delays for the equipment they supply.

- **Receiver Oscillator Errors**

While precise time standards at the Control and Space Segments of GPS are designed to keep user clock requirements to a minimum, receiver oscillators must provide enough stability to insure that they can be rated properly by GPS receiver software and that they provide a low noise timing reference. This is sometimes difficult to accomplish in high dynamic environments or when the receiver internal temperatures cannot be controlled or compensated for.

- **Geometric Dilution of Precision**

Geometric Dilution of Precision (GDOP) is a measurement of the sensitivity of a receiver position or time estimate to changes in the geometric relationship between the receiver position and the positions of all of the SVs used to form the position or time estimate. If the SVs used for a navigation solution were all in about the same place in the sky, directly above a receiver position, for instance, the position solution for height would be less sensitive to pseudo-range changes than would the poorly defined (diluted) solution for horizontal position. If the SVs were distributed around the field of view of the receiver, horizontal and vertical positioning would be more equally sensitive to pseudo-range changes.

GDOP is a dimensionless multiplier that can be used to estimate the effect of pseudo-range errors on a complete position and time solution. The single GDOP parameter is the square root of the sum of the diagonal terms of the covariance matrix that is formed from the inverse of the matrix of directional derivatives for each of the SV positions and pseudo-ranges used in the position solution. For a specified receiver position and a set of SVs, GDOP can be separated into three-dimensional position (PDOP) or spherical (SDOP) dilution, two-dimensional horizontal (HDOP), or one-dimensional vertical (VDOP) or time (TDOP) estimates. These separate components of GDOP are formed from covariance terms and so are not independent of each other. A high TDOP (time dilution of precision) in a navigation receiver will eventually influence position errors as erroneous receiver clock bias estimates are used to correct pseudo-range measurements.

4. GPS Receiver Types

The evolution of GPS receiver technologies and applications has resulted in different types of GPS receiver. Code and carrier tracking, sequential and multiplexed, single and parallel channel receivers exist for navigation, surveying, and time and frequency applications.

4.1 Code Tracking and Carrier Tracking

Code and carrier tracking are two different GPS signal tracking techniques. Most navigation receivers use code tracking to measure receiver to satellite range. GPS survey receivers, or carrier-tracking receivers, also track the phase of the carrier signal to provide a more precise measurement of the change in range to the satellites. A Doppler shift on the carrier signal results from the rate of change of the range from satellite to receiver. Most navigation receivers measure and track the Doppler frequency of the carrier signals and maintain sufficient phase lock on the carrier signal to recover the Navigation Message data bits and smooth code tracking measurements, but navigation receivers do not always establish or maintain phase lock on the carrier signal with sufficient accuracy or precision to make useful carrier-phase measurements.

- **Code-Phase Tracking**

The GPS signals consist of microwave radio signals modulated by pseudo-random bit streams and the Navigation Message. In code tracking GPS, the PRN codes (C/A-code or P(Y)-code) from the SVs are compared with identical PRN codes produced within the receiver that are shifted in time until the sequence of bits (chips) in the receiver is correlated (aligned in time) with the sequence of bits from the SV.

When PRN codes are aligned, the received signal carrier is reconstructed and measurable signal power can be detected. At perfect alignment signal power is at a peak. In order to arrive at an alignment that maximizes correlation in a way that is independent of changing signal strengths, receivers search for an alignment that produces an equal signal strength when code alignment is shifted back and forth around the correlation peak. By tracking at the PRN code alignment that results in equal signal power from alignments that are early and late by some equal spacing (usually one or one-half chip), it is possible to maintain code-phase tracking to small fractions of an individual code chip. The C/A-code bit period is just under 1 microsecond (~978 nanoseconds) and it is possible to correlate the receiver signal to within a few hundredths of a chip (~10 nanoseconds). When averaged over several millisecond C/A-code periods, this code-correlation time is the basis for the pseudo-range measurement for each SV (10 nanoseconds of correlation time is equal to about 3 meters of range). As suggested in section 2.6, the pseudo-range is so named because it is a measure of relative range, or range combined with receiver clock bias error, to each tracked SV. A set of four pseudo-ranges is sufficient to resolve this receiver clock bias and the actual ranges at the time of transmission from each SV. This results in a correction to the receiver clock as well as the position of the receiver antenna in three dimensions.

- **Carrier-Phase Tracking**

Early in the GPS testing period it was determined that the carrier signals themselves could be used to measure relative position. The GPS carrier frequencies are spread by the modulating PRN codes. When correlated with the proper receiver generated PRN code correctly aligned in time, the carrier signals are de-spread, or reconstituted, and are available for carrier phase tracking. Using phase-locked loops, the carrier signals can be tracked to a precision of fractions of a carrier wavelength. The L1 wavelength is about 19 centimeters and can be tracked in low noise situations to a few hundredths of a wavelength. Code tracking depends on PRN code alignment and time measurements with respect to the known start time of the periodic bit sequences. When carrier tracking, the receiver has no such start time or time reference to use. To make use of carrier tracking information, a receiver at a reference location tracks the same SV carrier signals that are measured by another receiver at a remote location. As the SV-to-receiver range changes due to the motion of the SV in orbit, changes in carrier phase are measured over time (a few seconds to many minutes). The difference between carrier phase changes at the reference station and carrier phase changes at the remote station are resolved through software techniques, accounting for integer wavelength ambiguities, into the position differences (in three dimensions) between the two sites. By measuring these changes at the same time from two GPS SVs, the receiver clock errors in the two receivers can be removed from the solution.

4.2 Receiver Channels

GPS signals are acquired and tracked by hardware and software techniques that vary considerably from receiver to receiver. Often it is difficult to tell from vendor specifications the exact nature of the receiver architecture. While receiver architecture is an indication of receiver capabilities, often functional specifications are more relevant in selection of receivers.

Early GPS receivers used a single analog hardware channel to track each SV. These multi-channel, parallel-tracking receivers were large and expensive. Later receivers were designed to use a single hardware channel either sequenced at a slow rate (more than a 20-millisecond, one data-bit period) between SVs, or multiplexed (sequenced at a fast rate, tracking each SV at least once within a 20-millisecond, one data-bit period). Next generation receivers were designed with two or three hardware channels, deployed in parallel for some tasks, and sequenced, or even multiplexed in other situations. Modern receivers are largely digital in design (replacing the analog circuitry in early designs with sampled data techniques). These receivers use software-based digital signal processing techniques, ranging from single channel receivers that track up to eight SVs in a variation of sequencing, to many-channel (twelve or more) parallel channel receivers. Modern integrated circuit chip sets have replaced the large and expensive parallel hardware channels.

In early receivers, the number of parallel channels was an indicator of both cost and quality. A few channels, sequencing through the SVs, allowed for a cheaper receiver but at the cost of reduced accuracy in dynamic or high-noise situations. Now the user must do careful comparison of receiver specifications and insist upon performance guarantees in the application environment, rather than rely on receiver type as a reliable guide to performance.

4.3 Navigation, Surveying, and Time and Frequency Receivers

Navigation receivers are divided into PPS (P(Y)-code) and SPS (C/A-code) receivers. P(Y)-code military receivers are equipped with Security Modules that require cryptographic keys and that convert the Y-code back into the P-code, as well as remove the effects of Selective Availability. These are limited in distribution to authorized agencies. SPS civil receivers tracking the C/A-code are available worldwide from a number of vendors. Ranging in price from $200.00 to several thousand dollars, the capabilities of these receivers often include airport data, mapping systems, course-deviation indicators, and serial-communications outputs for use with display systems or steering devices.

Land surveying has experienced a revolution since the introduction of GPS survey receivers. As outlined in section 4.1, these carrier phase tracking instruments gather precise sub-centimeter carrier phase data at a reference position and from a remote receiver. Carrier tracking techniques are differential in nature. Differential techniques, outlined in section 5.3, rely on differences in measurements between those taken at known, or reference, locations and measurements taken at the same time at unknown, or remote, locations. In carrier tracking applications software packages are required to convert differences between signals at a reference location and a remote location to differential position information.

Recent advancements in hardware and software have made it possible to conduct precise (millimeter) surveys even when the remote receiver is moving. There are a limited number of survey type P-code receivers that, while not equipped to track the encrypted Y-code, can make use of dual frequency ionospheric corrections and the P-code during those times when Anti-Spoofing is not implemented. Other survey receivers make use of codeless techniques that compare bit edge timing without decryption, to estimate ionospheric delays from the L1 and L2 signals.

Time and frequency receivers are designed for the control or measurement of time, time intervals, and frequency standards. These receivers usually process GPS signals using special techniques that assume a known, fixed position. While some are capable of being used for navigation, these receivers usually are not suitable for operation in a dynamic environment. In a recent survey of GPS manufacturers (GPS World 1995a), twenty-nine vendors identified themselves as producers of GPS time and frequency receivers. Ninety-four receivers were characterized as having multiple applications including time and frequency, while twenty-eight were identified as time and frequency receivers. Prices were provided for fifty-six receivers and ranged from $150 (for 1000 unit quantities) to $62,000 each and with an average price of $10,500. Stated accuracy figures for single receiver time measurements (without selective availability) ranged from 10 to 1,000 nanoseconds. Post-processed differential time accuracy claims ranged from 1 to 300 nanoseconds.

5. GPS Receiver Principles

GPS receivers select satellites for tracking, acquire the SV signals, process them to extract range measurements, and decode the navigation message containing clock and orbital data for the SVs. Receiver software processes include time and position determination through a variety of techniques.

5.1 SV Selection and Signal Acquisition at Receiver Startup

The GPS Navigation Message sends SV almanacs for each operational SV. These almanacs are orbital data sets that describe the orbits of each SV in an abbreviated form for use in predicting approximate position and Doppler shift for each SV. The almanac data is used along with an initial estimate of receiver position to predict the set of GPS SVs that might be visible at the receiver site. For receivers that track all SVs in view, either sequentially or in parallel, no further selection criteria are required.

For receivers that limit the set of tracked SVs, selection of the subset of SVs that offers the user the best performance is usually accomplished by selecting the subset of SVs that gives the lowest GDOP. For a timing receiver that may track the SV at the highest elevation (for lower bias errors and noise from the propagation path), the selection process may be more complex, requiring selection of the best subset of SVs for use in integrity monitoring (error checking) or continuous positioning while making time measurements.

Most receivers also use the almanac data to compute the Doppler shift on the carrier frequencies that occur due to the range rate from the movement of the SV as it orbits. Doppler shift estimates can aid in acquisition by presetting tracking loop frequencies to those expected for each SV, allowing the receiver to search for GPS SV signals in narrow bandwidths around the expected frequencies.

At power on, GPS receivers may take from a few seconds to many minutes to provide useful position outputs. If a receiver has current almanac data and a good position estimate (within a few kilometers), it might be possible to acquire, track, decode the Navigation Message, and provide position and time within thirty seconds or less. With no almanac data, or an incorrect position estimate, a receiver could take as long as a half an hour to provide correct position and time. By entering a correct position into the receiver on a first-time startup, the user will decrease the time required to search for satellites and begin normal operation.

The ionospheric model and GPS-UTC time correction parameters are transmitted every 12.5 minutes by each satellite and a receiver that makes use of them for precise time control might not provide a corrected output for as long as 12.5 minutes after powering up.

- **Positioning**

Positioning software in GPS receivers uses measured pseudo-ranges, SV clock corrections, SV ephemeris data, and an estimate of receiver position to compute a correction to receiver position. Pseudo-range measurements are formed from C/A-code (or P-code) arrival times. Four SV measurements are required for an independent solution for three position-dimensions and time. If the receiver clock errors or any of the three position-dimensions is known three SV measurements can be used to complete the solution for the remaining unknowns. In some cases height above the reference ellipsoid is known and can be used to allow three-SV solutions. Any errors in fixed height will be distributed into the horizontal position and time estimates.

- **SV-Time to GPS-Time**

The measured pseudo-ranges are each corrected for the SV-Time to GPS-Time correction that is broadcast by each SV in the clock correction subframe (Figure 4). Each 300-bit subframe is transmitted with the rising edge of the first bit marking a six-second interval of SV-Time. Each C/A code epoch (the moment when the code begins to repeat) is transmitted at an integer millisecond of SV-Time. The SV-Time-GPS-Time correction provides the offset and drift rate from a clock correction epoch for the SV, providing a correction from SV-Time to GPS-Time for the pseudo-range measurement for that SV.

- **SV Position from Ephemeris Parameters**

For each SV used in the position solution, an SV position at the time of pseudo-range transmission is computed from the orbital parameters broadcast by each SV. These ephemeris data sets describe the orbits of each SV for a period of a few hours. Given the GPS time of transmission, the ephemeris parameters are used in an ephemeris to SV position algorithm. The result is an Earth-Centered Earth-Fixed X, Y, and Z position for the SV at the moment it sent the related C/A-code or P-code signal.

- **Relativistic Effects**

Each pseudo-range is corrected for relativistic effects. The effect of the velocity of the SV toward the earth in its orbit is computed from the ephemeris data. A relativistic correction must also be applied to account for the rotation of the earth during the time of signal propagation. This “Sagnac effect” is dependent on both SV and receiver position. The magnitude of these effects can reach hundreds of nanoseconds.

SV 8: SUBFRAME 1

WORD	BITS	#1-8	#9-16	#17-24	#25-30
1	1-30	**[10001011]**[1]	11000000	00111111	101000
2	31-60	**[00110101**	**10110001]**[2]	10000100	110000
3	61-90	00111010	01010011	00000000	011000
4	91-120	01011000	01001101	11111100	010101
5	121-150	11011010	10110101	10100010	000101
6	151-180	00001111	10001111	01101010	010100
7	181-210	00111010	00111000	11111101	001001
8	211-240	00101001	**[00101001**	**01001111]**[3]	010100
9	241-270	**[00000000]**[4]	**[00000001**	**10110000]**[5]	011101
10	271-300	**[01010010**	**10100111**	**011100]**[6]00	00110**0***↑

[1] PREAMBLE: 10001011

[2] TIME OF WEEK (t): 00110101 10110001 1 = 27491 6-second subframes = 164946 seconds = SV time at end of bit 300* (↑)

[3] t_{oc}: 00101001 01001111 (scale 2^{4}) = 169200 seconds

[4] af2: 00000000 (scale 2^{-55}) = 0.0 sec/sec^{2}

[5] af1: 00000001 10110000 (scale 2^{-43}) = 4.91127138959 E-11 sec/sec

[6] af0: 01010010 10100111 011100 (scale 2^{-31}) = 6.30600377918E-04 seconds

(Δt_r = relativistic correction)

ΔTsv = af0 +af1 (t-toc) +af2(t-toc)^{2} + Δt_r = 630.391 microseconds +Δt_r

GPS Time at end of bit 300* (↑) = t + ΔTsv = 164946.000630391 seconds

Figure 4.

- **Directional Derivatives and the Position Solution**

Positioning algorithms are receiver dependent, but most develop a matrix of directional derivatives from the positions of the SVs with respect to a receiver position estimate. Usually these derivatives assume a circular orbit and so are not exact representations of the change in receiver X, Y, and Z with respect to pseudo-range estimate errors. An iterative position solution is usually accomplished by applying the difference between observed and predicted pseudo-ranges to a set of *n* (four or more) equations in four unknowns (receiver X, Y, Z and receiver clock bias). Position solutions converge to a constant value resulting in an estimate of receiver position and clock bias. Other implementations use non-iterative methods involving more complex formulations that result in a single solution for each set of measurements.

For a receiver navigating in a dynamic environment, the position solution is usually accomplished by incorporating the directional derivatives and pseudo-range measurements within a Kalman filter, or other predictor-corrector filter, that predicts position of a receiver experiencing velocity, acceleration and, in some implementations, jerk.

5.2 Direct-Reference Time and Frequency Measurements

In receivers designed for time and frequency applications, position is usually either fixed at a known set of geodetic coordinates or the receiver is assumed to be stationary and determines its own position. Rather than use filtered pseudo-range measurements to determine position as is done in a navigation receiver, these receivers use these measurements and a known position to control or measure local time or frequency standards. One pulse per second (1PPS) electrical signals, the electrical output of a frequency standard such as a 10 MHz sine wave, or some form of time code signal controlled by a 1PPS signal is produced.

Several different methods are used to transfer time from a reference standard through GPS to the user receiver. Real-time systems usually depend on some form of direct-reference time transfer.

- **Direct Reference**

A GPS receiver can track the GPS satellites and recover precise time from one or a set of satellites using the direct-reference technique. If the position of the receiver is accurately known, one SV signal will suffice for setting GPS-Time or UTC in a receiver. For a receiver without a previously known position, position from a GPS navigation solution can be used but the resulting time estimate will reflect any errors in the GPS-derived position solution. For a C/A-code receiver operating under SA the position can dither by 100 meters (95%) resulting in GPS time accuracies of around 330 nanoseconds (95%).

For a receiver in a known location with respect to the GPS geodetic datum (WGS-84) the errors can be less, but if the time is converted to UTC by the receiver using the broadcast conversion parameters the user should be aware that the broadcast parameters are only specified provide conversion to within 100 nanoseconds (Anon 1987, 3.3.4).

5.3 Differential Techniques

For both code-phase tracking navigation and carrier-phase tracking survey techniques, bias errors can be removed or mitigated by the use of differential techniques.

- **Post-Processed Precise Ephemerides**

Some GPS position techniques make use of precise ephemeris data that is published by public and private agencies from the measurement of GPS signals at multiple reference locations. These data sets are available from a agencies such as the International GPS Service for Geodynamics and the U. S. National Geodetic Survey within a few days or weeks of their reference times. Precise orbital data used in post-processed position solutions can improve the accuracy of both code and carrier-phase derived solutions (Lewandowski, Petit, and Thomas 1991, 3).

- **Differential GPS (DGPS)**

Selective Availability errors are correlated to a large extent for receivers within a few hundred kilometers of each other. For code tracking techniques, the ionospheric errors can be considered common to sites separated by a few hundred kilometers. Carrier tracking receivers can resolve differences in integer carrier wavelengths for receivers located within twenty to thirty kilometers of each other. Differential GPS (DGPS) is based on the assumption that bias errors common to two receivers, one a reference receiver at a known location, the other a remote receiver at an unknown location, can be measured at the reference receiver and applied to the remote receiver. DGPS techniques are based on the correction of individual SV pseudo-ranges or SV carrier-phase measurements. While it would be possible to apply a simple position correction from the reference receiver to the remote, both receivers would have to be tracking the identical set of SVs with identical GDOP components for the position solution transfer to be effective. While this common-view technique can work for specialized applications were great care is taken to track the same set of SVs over identical time periods, for general-purpose DGPS positioning this technique is not recommended. In most DGPS positioning systems the bias errors in each SV signal are measured at the reference receiver, which either sends corrections in real time to the remote receiver, or records the corrections for later application in post-processing software. In the remote receiver, or in post-processing software, the pseudo-range corrections are applied to the remote measurements prior to the formation of a position solution.

- **Interferometric Processing**

Measurements of crustal movements of the earth, earthquake fault line monitoring, and precise position transfer to isolated islands are possible using GPS interferometric techniques. In these special-purpose differential techniques, recordings of the pseudo-random codes and carrier-phase measurements on the GPS signals from distant sites are correlated and used along with precise ephemeris data in a post-processed mode to achieve position estimates in the centimeter range over thousands of kilometers. Global networks of carrier-phase tracking receivers are used in these processes.

- **Common View**

Not usually suitable for control of real-time systems or for positioning systems, common view measurements are often used to transfer precise time from one location to another. Two receivers, both at known fixed positions, measure signals from a single satellite over the same carefully chosen observation period. Both receivers collect and filter data with the same methods. The clock errors at the location with the reference standard are then transmitted to the other site, allowing the remote site to correct a clock with accuracies that have been obtained in the 8 nanosecond range for 1000 kilometer baselines and 10 nanoseconds for 5000 kilometer baselines (Lewandowski 1993, 138).

6. GPS Time Dissemination from Global Standards to the User Applications

The time available from a GPS timing receiver is traceable to global time standards. The time signals are linked by the Control, Space, and User Segments of GPS from these standards to the final timing application (Dana and Penrod 1990).

6.1 GPS-Time Steering

GPS-Time is controlled so that it maintains a close relationship to Universal Time Coordinated (UTC).

- **UTC (BIPM) to UTC (USNO-MC)**

The international standard for Universal Time Coordinated is maintained by the Bureau des Poids et Mesures (BIPM) in Sevres, France. This UTC (BIPM) is the result of a weighted average of about 200 clocks distributed worldwide (Thomas and Allan 1993). The U.S. Naval Observatory maintains a Master Clock (MC) that represents the time standard UTC (USNO-MC) that is kept within 100 nanoseconds of UTC (BIPM).

- **UTC (USNO MC) to GPS (CC)**

The USNO monitors the GPS SV signals against the Master Clock UTC(USNO MC) and provides clock corrections to the GPS Master Control station that keeps time as the GPS composite clock GPS (CC).

- **SV-Time**

Each SV transmits PRN codes aligned with that SV's clock. This space vehicle time is termed SV-Time. Measurements of the difference and the rate of change of the difference between each SV-Time and GPS (CC) are incorporated into the clock correction parameters sent in the Navigation Message by each SV.

6.2 Transfer of GPS Time Signals to the Receiver

The GPS SVs receive data uploads from the ground antennas. Ephemeris and clock correction data are rebroadcast by the SV in 12.5 minute Navigation Messages.

The L1 and L2 carrier signals are modulated with the PRN codes and the Navigation Message. The resulting spread spectrum signals are transmitted from the SVs toward the earth.

The receiver antenna and antenna cable transmit the spread spectrum signals to the receiver. The propagation time of the signal depends on the location of the phase center of the antenna and the type and length of the antenna cable. Low noise amplifiers and filters are used to condition the signal from the antenna. If automatic gain control is employed, the delays through variable gain stages must be accounted for.

6.3 SV Code Correlation in the GPS Receiver

The spread spectrum signal is mixed with a replica of the PRN code (C/A or P(Y)-code), de-spreading the signal and reforming the carrier signal when the PRN code(s) are aligned. Maximum signal strength in the de-spread signal is used to indicate code-phase lock.

The C/A-code repeats each millisecond. The receiver shifts the start time of the internally generated C/A-code until maximum correlation is reached. This C/A-code start time shift is the raw pseudo-range measurement. As measured by the C/A-code start time this raw pseudo-range represents some fraction of a millisecond. Tracking of the L1 carrier frequency allows demodulation of the Navigation Message bits and can provide an estimate of the rate of change of the C/A code that can be used to smooth the raw code-phase measurements.

6.4 Navigation Message Decoding and Application

The 50 Hz Navigation Message data bits are detected and tracked, providing a stream of GPS data bits. These data bits are aligned at time of transmission with the C/A-code start time, with each data bit transition coinciding with the twentieth C/A-code epoch.

The receiver uses the arrival time of data bit edges to resolve the raw, fractional millisecond pseudo-range into a pseudo-range with a twenty millisecond range ambiguity.

- **SV Data-Bit Frames and Subframes**

The Navigation Message consists of a series of data frames and subframes. A data frame is a sequence of five 300-bit subframes. Each subframe is made up of ten 30-bit data words. Each 300-bit data subframe is marked by the occurrence of a special preamble pattern. SV-Time is transmitted by each subframe as the integer number of six seconds marked by the rising edge of the first C/A-code transition associated with the first bit of the following subframe. This allows the receiver to resolve the twenty-millisecond ambiguity remaining in the pseudo-range.

- **Parity Algorithm and Data Bit Parsing**

Each 30-bit data word contains 24 bits used for GPS parameters and six bits used for parity checking and error correction. Starting at the beginning of a subframe, each word is rectified (inverted or not) based on the bit preceding the word. The parity bits are computed by the receiver and compared with the received parity bits. Identical parity bits provide a high degree of confidence in the received bit pattern. If not identical to the transmitted parity bits, single bit errors can be corrected by the parity algorithm.

Once data bits have been parity checked and rectified, the data bit subframes can be parsed by the software into GPS parameters. Each subframe contains specific parameters, packed and scaled for efficient storage in the 1500 bits of a data frame.

6.5 Subframe Contents

Subframe one contains the SV clock correction parameters, the GPS week number, SV health, and other system parameters. Subframes two and three contain the ephemeris parameters (orbit descriptions) for the SV. Subframes four and five are transmitted in consecutive pages, 1 through 25 over the length of the 12.5-minute 25-frame Navigation Message. Almanac data for each of the constellation SVs are transmitted by each SV within every complete Navigation Message.

Subframe four, page 18, contains both the GPS ionospheric model and the GPS-Time to UTC correction algorithm parameters (Figure 5). The current leap second offset is transmitted as an eight-bit two’s complement number of seconds. The GPS-UTC offset and offset rate are transmitted as the A0 and A1 parameters. The A0, time offset, parameter is a 32-bit two’s complement value with precision of about one nanosecond. The A1 parameter is transmitted as a 24-bit two’s complement number representing the rate of change of the GPS-UTC offset to a precision of about 10^{-15} seconds per second.

6.6 Determining GPS Time and Receiver Clock Bias

Clock correction data is used to correct the measured pseudo-range, time tagged with SV-Time, to a measurement tagged with GPS-Time. Ephemeris data is used with this GPS-Time to determine the position of the SV at the time of transmission.

- **Receiver Antenna Position**

For a timing receiver, the receiver antenna position is fixed and is used to compute a range estimate to the SV from the line of sight path to the SV at the time of transmission.

- **Propagation Time Estimate**

The range to the SV is converted to a propagation time estimate by multiplying the range by the speed of light. This estimate is then corrected by adding antenna cable length delay and internal receiver delay (provided by the manufacturer), the ionospheric and tropospheric delay estimate, and the relativistic Sagnac effect.

- **Receiver Clock Bias**

Since the receiver clock offset is originally unknown, each code phase measurement contains both this receiver clock bias and the range to the SV. The mean of the differences between each predicted and observed SV range represents an estimate of the receiver clock offset. Changes over time in that offset form clock drift estimates. Clock drift can also be estimated from the difference between observed and predicted SV Doppler shift. These offset and offset drift measurements are used to control or measure time and frequency standards.

- **GPS-Time to UTC Conversion**

If required by the application, GPS-Time can be converted to UTC by application of the GPS-UTC parameters sent in the Navigation Message.

6.7 Coupling to Real-Time Applications

To make use of controlled time or frequency signals they must be transferred to the user application. Control of an electrical 1PPS signal or frequency standard or a time code signal transmitted over a data link are common distribution techniques. Modules which produce time code signals are usually under the hardware control of a 1PPS signal that is produced or steered by the GPS timing receiver.

Real-time GPS timing users should be aware that many GPS time control and frequency control techniques provide signals that are not usable at their specified accuracies for many hours. Some SA filters and high-precision timing outputs may require as many as twelve hours to settle to appropriate levels.

Coupling to user computer equipment can be simplified by the use of GPS receivers that operate as plug-in cards that fit within personal computers (Hough 1991). With careful measurement of the latency time and repeatability required to read and transfer the GPS time measurements on the PC bus, remote PC applications can be synchronized.

Many timing receivers distribute time code signals over RS-232 or IEEE-488 interfaces in a variety of formats. Some provide Inter-Range Instrumentation Group (IRIG) signals in different IRIG formats. Real-time computer systems can be interfaced to some GPS receivers through Ethernet connections and by utilizing Network Time Protocol (NTP) (Mills 1991).

One major transcontinental telecommunications network is based on a geographically distributed set of 16 Primary Reference Clocks (PRCs), each synchronized by a GPS receiver, that controls a network of secondary nodes. PRCs are inter-compared and timing is distributed throughout the system by DS1 optical fiber networks (Butterline 1993). One European local code division multiple access (CDMA) mobile telecommunications network uses single highest SV common-view time transfer to maintain synchronization between cells in a limited area (Werner 1993).

6.8 Receiver Status and Alarms

Of particular importance to the real-time GPS timing user is the question of what the receiver and the associated equipment will do when the GPS fails. Most receivers provide some kind of coasting or fly-wheeling capability during periods of system failure. It is important to be aware that the GPS receiver may continue to provide timing signals during those periods that may be indistinguishable from normal signals. When the GPS returns to full capability after an outage, it may be many hours before the receiver can again provide the highest levels of accuracy.

Time-code data or hardware signals must be used in conjunction with appropriate alarms. Some receivers provide visible alarms on the receiver front panel that are also linked to hardware connectors that can provide alarm signals to remote application equipment. Many provide data ports from which alarm or status indicators can be read. Automatic alarm or status monitoring should always be associated with the use of GPS for control of real-time systems.

7. Receiver Enhancements for Timing Applications

Differences exist in receiver hardware and software. Many techniques used to improve GPS measurements are incorporated into receivers in proprietary software enhancements. Improved timing capabilities may be available for existing receivers through procurement of software updates for the manufacturer.

- **RF Interference Monitoring and Mitigation**

Local radio frequency (RF) signals can cause errors in GPS measurements. Techniques are available for detecting and in some cases removing narrow-band local RF interference from the signals picked up by the GPS antenna (Ward 1995).

- **Carrier Smoothing of Code Phase**

Most GPS receivers now implement some form of smoothing of code-phase measurements by combining raw code phase measurements with integrated Doppler measurements. The carrier phase rate of change (SV Doppler shift) is an indicator of the rate of range change to the SV. By applying a carrier-derived phase rate correction to the code-phase tracking filter, raw pseudo-ranges can be smoothed.

- **Code and Carrier Phase Differences**

The difference between carrier phase and code phase range-rate estimates is an indicator of the effect of multipath on the pseudo-range measurements. While not capable of removing the multipath errors, the code and carrier phase rate difference is valuable for evaluation of the multipath environment and for assistance in acceptable antenna placement.

- **Narrow Correlator Spacing**

Narrow correlator spacing is a method of aligning receiver and SV PRN codes by narrowing the time delay between samples taken early and late around the maximum correlation peak (Van Dierendonck, Fenton, and Ford 1992). In some cases noise and multipath error reduction is possible (Cannon and others 1994).

- **Single SV Tracking**

Timing receivers can operate using a single SV as it passes overhead, switching to another SV when appropriate. This single SV-Time control allows the use of the highest elevation-angle SV, keeping ionospheric delays to a minimum and insuring good visibility and high signal strength. The disadvantage of the single SV approach is that errors in an SV clock and range estimate will be directly linked to the receiver's time measurements. With a single SV there is no possibility of error detection other than the detection of step changes in the corrected pseudo-range. Errors that occur in the form of a slowly changing ramp are difficult to detect when tracking a single SV and when undetected will be incorporated into receiver control of the local time standard.

- **Ensemble Techniques**

Ensemble techniques, the use of more than the single SV required by a receiver with a known position for time estimates, can provide at least three advantages. With multiple measurements some degree of protection is afforded against errors from a single satellite, the step changes in time estimates that can occur when switching from one SV to another can be lessened, and it is possible to take advantage of redundant measurements to improve timing accuracy. While it is possible for low elevation angle satellites to introduce lower signal to noise ratios that may corrupt the ensemble measurements, with careful editing and the use of high elevation angle masks[2], ensemble measurements can enhance error immunity, reduce step changes in time estimates, and improve timing accuracy.

- **Receiver Autonomous Integrity Monitoring (RAIM)**

Receiver autonomous integrity monitoring (RAIM) techniques use the GPS signals from many SVs to provide an estimate of the probability of bias errors in each individual signal. Multiple SV tracking and associated RAIM techniques can detect step failures and some faster ramping errors. For a timing receiver with a known fixed position and a high quality internal oscillator, RAIM techniques can be particularly effective (King and others 1995).

- **Disciplined Oscillator (Smart Clock)**

For a timing receiver that may have access to a high quality clock, it is possible to use the precise time and frequency information from GPS to "learn" the characteristics of that clock over time. These "smart clock" or disciplined oscillator techniques may not only provide a high quality of RAIM capability, but can provide protection against GPS failures by allowing the time or frequency standard to operate during periods of GPS outages by learning both the temperature sensitivity and the aging characteristics of a quartz or atomic oscillator. One Russian telecommunications system uses a GPS receiver with an internal rubidium standard that is disciplined by GPS, providing 10^{-11} stability while realizing both cost and life expectancy advantages over cesium standards (Toolin 1992, 32).

- **Selective Availability Filtering**

Various techniques have been tried to mitigate the effects of SA. Because each SV signal is varied independently of the others, averaging of ensemble measurement is minimally effective over short periods of time. The SA variation from individual SVs tends to average toward a zero mean over periods of several hours. New techniques, sometimes referred to as enhanced GPS (EGPS), reduce SA errors by filtering the pseudo-ranges from each SV using proprietary methods (Allan and Dewey 1993, Allan 1995, and Allan and others 1995).

- **Data Editing and Filtering of Step Changes**

No matter what techniques are used to derive time estimates from the GPS satellite signals, step changes in measurements will occasionally occur. When this happens, difficult data editing and filtering issues arise. Receiver software must either ignore the step change, set receiver time to this new estimate, or slowly move the receiver time estimate to a new one. The diagnosis of a problem and the selection of a suitable corrective action are both difficult problems for the GPS software designer (Barnes 1995).

8. GPS Time Dissemination Failure Modes

While some GPS time dissemination failure modes are difficult to ascribe to a particular failure source, most reported problems are a direct result of problems associated with one of the three fundamental divisions: the Control, Space, and User Segments of GPS.

8.1 Control Segment

Control Segment failure modes are those resulting from hardware, software, or procedural errors in the process of monitoring and controlling GPS.

There are reports of occasional unexplained system failures. Vendors with customers using receivers at many sites have reported simultaneous erroneous receiver outputs from different receiver models and brands, suggesting that either all the receivers were experiencing the same internal fault or that the system failed. Vendors argue that these specific failure modes have not been duplicated during receiver testing and have not reoccurred even though no changes have been made in receiver software or hardware.

- **Scheduled Maintenance**

Scheduled SV outages are reported by a Notice Advisory to NAVSTAR Users (NANU), issued by Master Control. These NANUs are available from the U. S. Coast Guard’s Global Positioning System Information Center (GPSIC) Bulletin Board Service (Anon 1992) and in the *Daily Time Differences, Series 4* published by the U. S. Naval Observatory. While most receivers allow manual deselection of SVs, it is operationally difficult to automatically introduce these scheduled events into the software of a timing receiver. If for some reason the SV is not marked as unhealthy within the Navigation Message during these maintenance periods, timing errors will likely result.

- **Unscheduled Events**

The monitor network is charged with the task of checking the broadcast data from each SV every 15 minutes. Emergency uploads may take place if transmitted data is out of tolerance. The length of time for a complete Navigation Message is 12.5 minutes. Should a timing receiver receive a complete Navigation Message containing errors undetectable by the receiver, timing errors can result. While a NANU may be published after the fact, indicating that an SV was “unusable for navigation” for a period, this offers no protection for the real-time user against these unscheduled events.

- **Blunders**

One report states that during a 1994 Christmas-week personnel shift change at the Master Control station the GPS Composite Clock drifted by more than a microsecond from UTC (Allan 1995).

In September of 1995, one of the Block I SVs had to be removed from service after timing receivers reported a three-millisecond timing error when tracking that SV. Master Control had been unable to upload control data to the satellite in order to correct the problem or set it to an “unhealthy” status. The problem in that SV’s rubidium clock was finally corrected and the satellite was returned to service (GPS World 1995b, 16).

- **SVs Out of View**

The current monitor network cannot “see” all of the GPS SVs at all times. When satellites are out of the view of ground monitor stations it can take many minutes for an out-of-tolerance condition to be noticed.

- **Time to Fix**

There are reports that it occasionally takes more than an hour for the Master Control station to flag an SV as unhealthy.

8.2 Space Segment

It is often difficult to tell whether a failure originated in the Control or Space Segment. Some SV failures have been reported but NANUs usually simply report that an SV was “unusable” for a period of time without any explanation.

In February 1993 an older Block I SV clock data bit error caused position errors of many kilometers in ground receivers. Although the timing error lasted for over an hour, the SV was still marked as healthy for a period of 45 minutes (Navin 1993). GPS Master Control released a NANU that simply stated “PRN03/SVN11 Unusable 19 Feb 1930 to 2045 UT” (USNO 1993).

While normal eclipse periods, when SVs are shaded from the sun by the earth, cause only small errors, there are reports of occasional 30 to 45 nanoseconds of range error after the transition back into sunlight, perhaps caused by the escape of water vapor from the SV. Another reported failure mode takes the form of clock jumps from changes in atomic clock control currents (Shank and Lavrakas 1994, 52).

8.3 User Segment

Receiver-based problems are associated with hardware, software, or procedural problems at the user site[3].

- **Antenna Placement**

Antenna placement is critical for GPS timing applications. The antenna must be able to view most of the sky from local horizon to horizon in all directions. This is especially important for receivers that use ensemble techniques or when the receiver is used to establish position. A GPS receiver requires an unobstructed line-of-sight path from the antenna to each GPS SV required for navigation or timing. Because the SVs move in orbit across the sky, buildings or terrain that block the view of the sky from the antenna location will have a serious impact on the receiver's ability to provide maximum accuracy twenty-four hours a day.

Local RF interference may affect some GPS antenna placements. Foliage can block or attenuate GPS signals, and an installation that works in the winter may begin to experience problems in the spring. Multipath problems may exist in the presence of local reflectors of the GPS signals. Nearby structures built after initial antenna placement may change the multipath environment as well as block portions of the sky. The GPS receiver must be connected to the GPS antenna by a cable. Roof access is required and may be hard to obtain due to physical obstructions or the objections of the building owners. Security problems may be associated with the necessity for connecting an antenna cable between a secure area and the antenna location. Long cable lengths introduce a delay which must be accounted for and may cause unacceptable signal strength losses. GPS timing users who experience problems that might be associated with antenna placement should seek assistance from receiver manufacturers.

- **Receiver Software**

The software in GPS receivers can cause failure modes. Over the history of GPS receiver development, many problems, some unique to specific designs and some common to various software approaches, have resulted in GPS timing and navigation errors.

Each 300-bit Navigation Message subframe begins with an eight-bit preamble pattern (10001011). In addition to the preamble, other fixed bit-patterns within the message can help synchronize the receiver to data bit subframes and frames. Early receivers sometimes found these patterns at other alignments with the Navigation Message resulting in mis-parsed and erroneous parameter values. Later designs reduced the chances of misalignment, but occasionally reports still surface of improper subframe synchronization.

Automatic gain control (AGC) software has been identified as the cause of occasional lockups of one GPS timing module. When large RF energy excursions reached the antenna preamplifier, AGC software caused a failure mode. To clear the problem, receiver power had to be turned off and back on, with a resulting loss in receiver timing outputs.

A software failure was reported last year (Brottlund and Harris 1995) that specifically related to UTC calculations. In the computation of the GPS-UTC offset, the correction offset and rate are referenced to a specific reference time. That time is transmitted in page 18 of subframe four as a time in seconds and a week number represented by eight bits (256 weeks). To resolve the correct untruncated week number, it is necessary to compare the truncated version with the current untruncated GPS week number given in subframe one. Because the UTC parameters are only specified to be updated every six days, the lower eight bits of the GPS week and the bits of the UTC reference week are not always the same. In September 1994, during GPS week 767, some receivers incorrectly identified the UTC week number by an entire 256 weeks, resulting in the calculation of a completely erroneous GPS-UTC offset and rate.

Other problems are related to receiver software and interpretations of the GPS Interface Control Document (ICD). Some early receiver designs failed to account for the Sagnac effect, mentioned in the ICD with the phrase “the user shall account for the effects due to earth rotation rate during the time of signal propagation so as to evaluate the path delay in an inertially stable coordinate system” (Anon 1987, 20.3.3.4.3.5). A lack of agreement on implementation was related to early differential receiver errors (Pietraszewski and others 1987, 249).

Bit 19 of the second word in each 300-bit subframe is identified in the ICD as the synchronization flag for the Block I satellites or as the anti-spoofing flag for the Block II satellites. Page 25 of subframe four contains an SV configuration code that identifies each SV as Block I or Block II type. There are reports that occasionally a Block II SV is identified as Block I while anti-spoofing is on for that SV. Bit 19 of word two is then used to flag the SV as not in synchronization, and the receiver software fails to use the SV for navigation or timing.

Receiver software failures and unforeseen interactions between Navigation Message content and receiver software will continue to occur as new generations of receivers are designed, the new Block IIR SVs are launched, and Navigation Message bits are used or redefined.

- **Geodetic Datum Selection**

Receiver position must be determined for a GPS timing receiver. With Selective Availability limiting the accuracy of most timing receivers, little attention has been given to the exactness of GPS receiver position estimate. Many manufacturers simply recommend that customers allow the receiver to estimate position. For more exacting requirements, the receiver position must be independently obtained and entered into the receiver.

Geodetic latitude and longitude must be referenced to a specific geodetic datum, the set of parameters that describe the size and orientation of the earth, in order to specify a precise location. The GPS reference datum is WGS-84. If the position for a receiver antenna is referenced to a different datum, the potential exists for as much as a one kilometer error. In the United States, a position in geodetic latitude and longitude referenced to the North American Datum 1927 can point to a position as much as 120 meters away from its location in WGS-84. For other geodetic datums, shifts between WGS-84 and the local geodetic coordinates must be computed from shift parameters or scaled from contour maps of datum shift estimates (Defense Mapping Agency 1987).

- **Geodetic Height**

Geodetic height is defined as the height above a reference ellipsoid, the ellipsoid of rotation upon which the geodetic datum is based. For some GPS receivers, it is necessary to provide the geodetic height of the receiver in the WGS-84 system. This is not equivalent to elevation above sea level, the parameter most often available to a timing user. The ellipsoid is only an approximation of the shape of the earth. The geoid is the equipotential surface of the earth's gravity field that best fits mean sea level. For the WGS-84 geoid there can be as much as a 100 meter separation between geoid height (approximately mean sea level) and height above the reference ellipsoid (geodetic height). Care must be taken to insure that receiver terminology is correctly understood and that antenna height is entered in the appropriate height system or errors as much as 100 meters (300 nanoseconds) could occur.

- **Time Distribution Problems**

One of the most difficult problems in applying the measurements of a GPS timing receiver is the distribution of time from the receiver to the user application. Timing signals that are distributed to applications must account for the time delays between receiver output and the application. In some cases the distribution time can be measured or computed. In other instances the distribution time may be variable. Software and hardware interrupt latencies can vary considerably in computer applications, and distribution systems may experience dynamic routing changes that will vary path length. In other situations, distribution methods may be frequency dependent and variable delays can result from changing dispersion characteristics of the distribution medium.

9. Conclusions

There are differences of opinion regarding the robustness of the GPS system. In discussions with design engineers with long experience in GPS time and frequency applications, one indicated his belief that "there is absolutely no better way to transfer time." During the same week another stated that "the GPS system is far from robust," while another said, "GPS is very robust." There does seem to be a common belief that the system is maturing rapidly and that the new receivers, making use of ensemble techniques and implementing RAIM schemes, will continue to improve GPS reliability.

The NANUs show that Control and Space Segment scheduled maintenance or unscheduled problems resulted in over 50 periods of SV unavailability during the first three months of 1995. Over half of those outages were unscheduled problems lasting from a few minutes to several hours. There is no comparable accounting of receiver-induced problems during the same period.

The GPS user is normally concerned with the reliability of the timing signals used by the final application, not with which GPS Segment was responsible for a particular problem. For potential GPS timing receiver users, careful selection of receivers based on how well they handle signal outages and errors from one or two SVs may be as important as the interfacing and accuracy specifications.

Potential users of GPS time dissemination methods should be aware that GPS is an ongoing process, subject to dynamic changes in procedures, hardware, software, and support[4]. New satellites are being developed by vendors who have not supplied GPS satellites in the past for deployment as replacements for the current generation. Changing domestic political balances can change funding priorities and affect GPS staffing and equipment support. International political changes can affect the way in which a DoD system is viewed from both U.S. and foreign perspectives (Allan 1995).

Changes in Selective Availability signal degradation levels can seriously impair or improve GPS timing capabilities. If rumored SA discontinuation occurs a new focus on error sources now masked by SA may result in a new generation of receiver designs. Interfacing applications to GPS timing subsystems is an area of on-going improvement. New methods for time dissemination from the GPS receiver to multiple interconnected user applications are needed. New GPS techniques, particularly those relating to carrier phase tracking, may improve accuracies available for some types of time transfer (Allan 1994). The combined use of GPS and the similar Russian GLONASS system (Gouzhva and others 1992) or the implementation of GLONASS receivers as replacements or as independent timing sources for GPS monitoring are possible improvements to stand-alone GPS (Gouzhva and others 1995).

The most important advice for GPS timing users in the real-time community is to use GPS as an additional input to the ensemble techniques that have already been developed to maintain synchronization between computer systems. GPS is indeed a source for very precise time and time interval standards. No other system can provide comparable precision and accuracy on a global basis. GPS is, however, subject to failure modes, failures that can and do occur at all stages of the GPS process. To allow GPS to become the single source for time keeping is to put too much faith in a complex process involving many levels of procedures, personnel, hardware and software systems, and user interfaces.

Acronyms

BIPM	Bureau des Poids et Mesures
C/A-code	Coarse Acquisition Code
CC	Composite Clock
CDMA	Code Division Multiple Access
DGPS	Differential GPS
DoD	Department of Defense
DOP	Dilution of Precision
DoT	Department of Transportation
FRP	Federal Radionavigation Plan
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
HDOP	Horizontal DOP
ICD	Interface Control Document
IRIG	Inter-Range Instrumentation Group
L1	1575.42 MHz GPS signal
L2	1227.6 MHz GPS signal
MC	Master Control
NAD-27	North American Datum 1927
NANU	Notice Advisory to NAVSTAR Users
NTP	Network Time Protocol
P-code	Precise-code
PDOP	Position DOP

PPS	Precise Positioning Service
PRC	Primary Reference Clock
PRN	Pseudo Random Noise
SDOP	Spherical DOP
SPS	Standard Positioning Service
SV	Space Vehicle
TDOP	Time DOP
USNO	U. S. Naval Observatory
UTC	Universal Time Coordinated
VDOP	Vertical DOP
WGS-84	World Geodetic System 1984
Y-code	Encrypted P-code

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Notes

1. The World Geodetic System 1984 (WGS-84) replaced WGS-72 as the reference geodetic datum for GPS on January 10, 1987.
2. An elevation mask is a user selectable limiting elevation angle with respect to the local horizon below which GPS SVs will not be used in a navigation or time solution. A typical default elevation mask value is five degrees.
3. Reports of receiver problems, generously supplied by vendor representatives, are presented here without reference to specific brands or receiver models.
4. Sources for GPS information continue to develop. *GPS World* and *Navigation: Journal of the Institute of Navigation* are good up-to-date references. Current GPS status is available from the USNO over the Internet, telnet to tycho.usno.navy.mil, login as 'ads' or by connecting through the World Wide Web URL: http://tycho.usno.navy.mil/gps.html. Other WWW sources are the University NAVSTAR Consortium at URL:http://www.unavco.ucar.edu and the University of New Brunswick at URL:gopher://unbmvs1.csd.unb.ca:70/hPUB.CANSPACE.GPS.INTERNET.SERVICES.HTML. The author maintains a GPS page at the University of Texas, URL:http://www.utexas.edu/depts/grg/gcraft/notes/gps/gps.html. The United States Coast Guard operates the GPSIC BBS at 703-313-5910 and the Navigation Center WWW site at: URL:http://www.navcen.uscg.mil/. Other Internet resources are listed in Langley (1995).

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