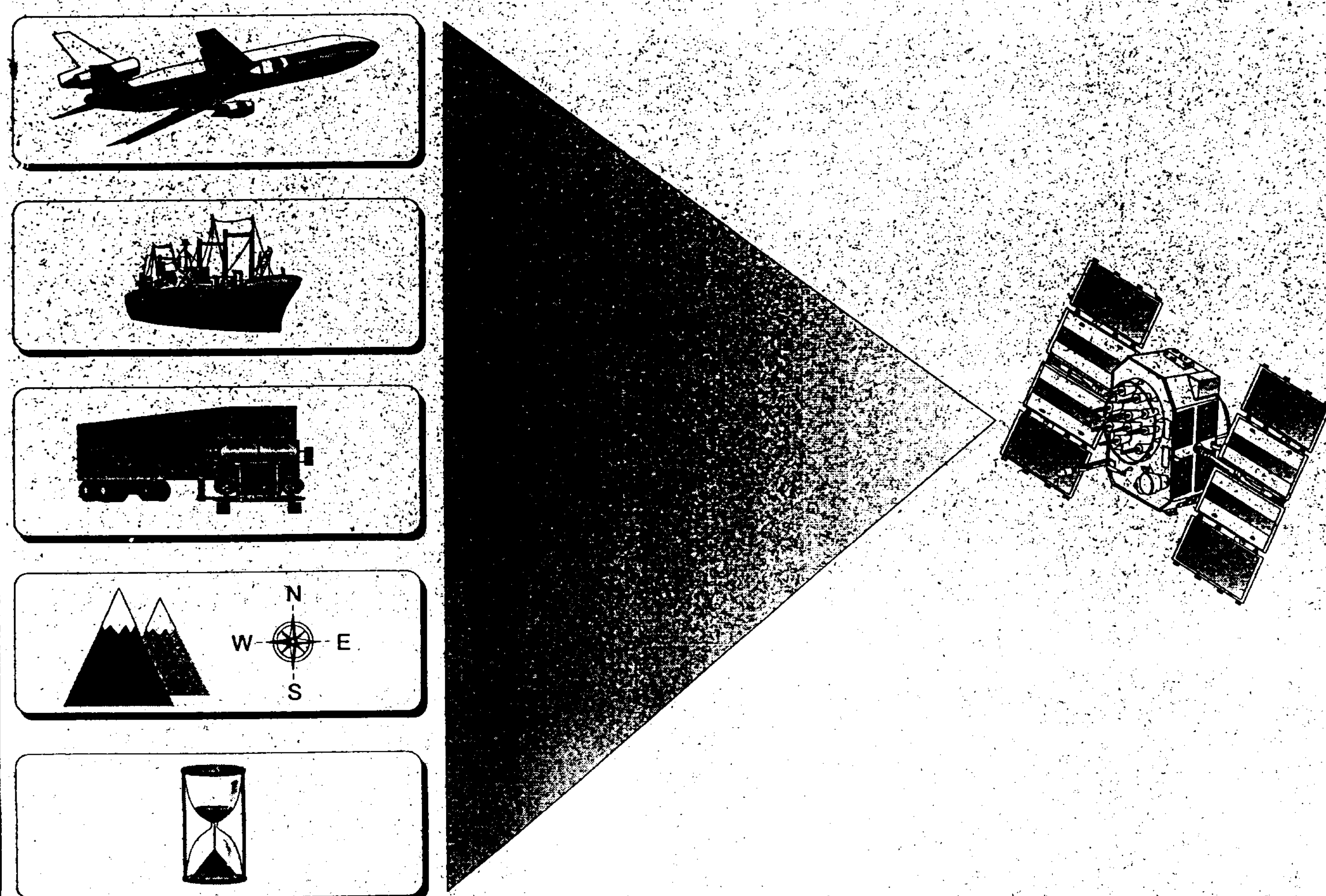
S-005

Global Positioning System
Standard Positioning Service

SIGNAL SPECIFICATION

GPS Civil Performance Standards



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COMMAND CONTROL, COMMUNICATIONS AND INTELLIGENCE

LETTER OF PROMULGATION

SUBJECT: Global Positioning System (GPS) Standard Positioning Service (SPS) Signal Specification

The attached document defines GPS services provided by the Department of Defense to the Department of Transportation to support the needs of civil users. It has been approved by the DoD Positioning/Navigation Executive Committee. Please refer any questions or comments, in writing, to the following:

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Attachment

GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE SIGNAL SPECIFICATION

November 5, 1993

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NOTE: Table of Contents for the Annexes are contained within each respective Annex.

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SECTION 1.0 The GPS Standard Positioning Service

The Global Positioning System (GPS) is a space-based radionavigation system which is managed for the Government of the United States by the U.S. Air Force (USAF), the system operator. GPS was originally developed as a military force enhancement system and will continue to play this role. However, GPS has also demonstrated a significant potential to benefit the civil community in an increasingly large variety of applications. In an effort to make this beneficial service available to the greatest number of users while ensuring that the national security interests of the United States are observed, two GPS services are provided. The Precise Positioning Service (PPS) is available primarily to the military of the United States and its allies for users properly equipped with PPS receivers. The Standard Positioning Service (SPS) is designed to provide a less accurate positioning capability than PPS for civil and all other users throughout the world.

1.1 Purpose

The GPS SPS Signal Specification defines the service to be provided by GPS to the civil community. This document is written to satisfy the following four objectives:

1) Specify GPS SPS ranging signal characteristics.

2) Specify SPS performance, given a receiver designed in accordance with this Signal Specification.

3) Standardize SPS performance parameter definitions and measurement methodologies.

4) Define SPS performance characteristics.

The Signal Specification consists of this document and three Annexes. This document specifies GPS SPS signal characteristics and the minimum requirements for receiving and using the SPS ranging signal. The Annexes provide technical data that quantifies SPS performance. Provided below is a definition of each Annex's purpose:

- **Annex A: SPS Performance Specification.** This Annex specifies GPS SPS performance in terms of minimum performance standards, and conditions and constraints associated with the provision of the service.

- **Annex B: SPS Performance Characteristics.** This Annex defines GPS SPS performance parameters and their characteristics as a function of time, user location, system design and changing operational conditions.

- **Annex C: Means of Measuring GPS Performance.** This Annex defines the specific measurement processes which a user must apply to evaluate GPS performance, in order to obtain results which are consistent with the parameter definitions and performance standards established in this Signal Specification.

1.2 Scope

This Signal Specification defines SPS ranging signal characteristics and minimum usage conditions. The Annexes establish the SPS performance which a minimally equipped SPS user can expect to experience anywhere on or near the surface of the Earth, and the means to evaluate that performance. SPS signal and performance specifications are independent of how the user applies the basic positioning and timing services provided. Performance specifications do not take into consideration the measurement noise or reliability attributes of the SPS receiver or possible signal interference.

This Signal Specification and the Annexes establish new definitions and relationships between traditional performance parameters such as coverage, service availability, service reliability and accuracy. GPS performance specifications have previously been made to conform to definitions which apply to fixed terrestrial positioning systems. The new definitions are tailored to better represent the performance attributes of a space-based positioning system. Refer to Annex B for a more comprehensive discussion of GPS performance parameter definitions and relationships.

Due to the nature of the system design and its operation, individual GPS satellite ranging measurements will not necessarily exhibit unchanging SPS ranging error statistics. Furthermore, the Department of Defense (DOD) does not guarantee that GPS ranging or positioning error statistics will remain stationary, or that individual satellite ranging error statistics will be consistent throughout the constellation.

The DOD will base its on-going measurement and assessment of all specified aspects of SPS performance on data gathered from Control Segment (CS) monitor stations. If the minimum performance standards are met at each of the monitor stations, the DOD will assume that standards are being met on a global basis. Geographic variations in performance will be taken into consideration in the assessment process.

1.3 GPS Policy

The policy of the United States Government regarding the provision and usage of the GPS Standard Positioning Service is as follows:

GPS is a DOD-developed, worldwide, satellite-based radionavigation system that will be the DOD's primary radionavigation system well into the next century. The operational capability of GPS is of significant interest to both civil and military users. The term Full Operational Capability (FOC) is of particular significance to the Department of Defense as it defines the condition when full and supportable military capability is provided by a system. GPS FOC will be declared by the Secretary of Defense when 24 operational (Block II/IIA) satellites are operating in their assigned orbits and when the constellation has successfully completed testing for operational military functionality. A Civil Initial Operational Capability (IOC) will be attained when 24 GPS satellites (Block I/II/IIA) are operating in their assigned orbits, are available for navigation use and can provide levels of service as specified below. Notification of civil IOC by the Secretary of Defense to the Secretary of Transportation will follow an assessment by the Air Force, as the system operator, that the constellation can sustain the stated levels of accuracy and availability throughout the civil IOC period. Civil IOC is planned to occur in 1993 and military FOC is planned in 1995.

Prior to civil IOC, GPS is considered a developmental system. System operation, including signal availability and accuracy, is subject to change at the discretion of DOD. Operations conducted using the developmental system are, therefore, subject to disruption if it is necessary to adjust system operating parameters in support of system testing. At civil IOC, the GPS will have achieved its earliest operational configuration and the Standard Positioning Service (SPS) will be available as specified below.

Subsequent to civil IOC, any planned disruption of the SPS in peacetime will be subject to a minimum of 48-hour advance notice provided by the DOD to the Coast Guard GPS Information Center (GPSIC) and the FAA Notice to Airmen (NOTAM) system. A disruption is defined as periods in which the GPS is not capable of providing SPS as specified below. Unplanned system outages resulting from system malfunctions or unscheduled maintenance will be announced by the GPSIC and NOTAM systems as they become known. The Coast Guard and the FAA will notify civil users when the GPS is approved for navigation.

THE STANDARD POSITIONING SERVICE: *SPS is a positioning and timing service which will be available to all GPS users on a continuous, worldwide basis with no direct charge. SPS will be provided on the GPS L1 frequency which contains a coarse acquisition (C/A) code and a navigation data message. SPS is planned to provide, on a daily basis, the capability to obtain horizontal positioning accuracy within 100 meters (95% probability) and 300 meters (99.99% probability), vertical positioning accuracy within 156 meters (95% probability), and timing accuracy within 340 ns (95% probability). The GPS L1 frequency also contains a precision (P) code that is reserved for military use and is not a part of the SPS. Although available during GPS constellation buildup, the P code will be altered without notice and will not be available to users that do not have valid cryptographic keys.*

1.4 Key Terms and Definitions

Terms and definitions which are key to understanding the scope of the GPS Standard Positioning Service are provided below.

1.4.1 General Terms and Definitions

The terms and definitions discussed below are used throughout the Signal Specification. An understanding of these terms and definitions is a necessary prerequisite to full understanding of the Signal Specification.

Standard Positioning Service (SPS). Three-dimensional position and time determination capability provided to a user equipped with a minimum capability GPS SPS receiver in accordance with GPS national policy and the performance specifications established in this Signal Specification.

Minimum SPS Receiver Capabilities. The minimum signal reception and processing capabilities which must be designed into an SPS receiver in order to experience performance consistent with the SPS performance standards. Minimum SPS receiver capabilities are identified in Section 2.2.

Selective Availability. Protection technique employed by the DOD to deny full system accuracy to unauthorized users.

Block I and Block II Satellites. The Block I is a GPS concept validation satellite; it does not have all of the design features and capabilities of the production model GPS satellite, the Block II. The FOC 24 satellite constellation is defined to consist entirely of Block II/IIA satellites. For the purposes of this Signal Specification, the Block II satellite and a slightly modified version of the Block II known as the Block IIA provide an identical service.

Operational Satellite. A GPS satellite which is capable of, but may or may not be, transmitting a usable ranging signal. For the purposes of this Signal Specification, any satellite contained within the transmitted navigation message almanac is considered to be an operational satellite.

SPS Signal, or SPS Ranging Signal. *An electromagnetic signal originating from an operational* satellite. The SPS ranging signal consists of a Pseudo Random Noise (PRN) Coarse/Acquisition (C/A) code, a timing reference and sufficient data to support the position solution generation process. A full definition of the GPS SPS signal is provided in Section 2.

Usable SPS Ranging Signal. An SPS ranging signal which can be received, processed and used in a position solution by a receiver with minimum SPS receiver capabilities.

SPS Ranging Signal Measurement. The difference between the ranging signal time of reception (as defined by the receiver's clock) and the time of transmission contained within the satellite's navigation data (as defined by the satellite's clock) multiplied by the speed of light. Also known as the *pseudo range*.

Geometric Range. The difference between the estimated locations of a GPS satellite and an SPS receiver.

Navigation Message. Message structure designed to carry navigation data. This structure is defined in Section 2.4.

Navigation Data. Data provided to the SPS receiver via each satellite's ranging signal, containing the ranging signal time of transmission, the transmitting satellite's orbital elements, an almanac containing abbreviated orbital element information to support satellite selection, ranging measurement correction information, and status flags.

Position Solution. The use of ranging signal measurements and navigation data from at least four satellites to solve for three position coordinates and a time offset.

Dilution of Precision (DOP). *The magnifying effect on GPS position error induced by mapping* GPS ranging errors into position through the position solution. The DOP may be represented in any user local coordinate desired. Examples are HDOP for local horizontal, VDOP for local vertical, PDOP for all three coordinates, and TDOP for time.

SPS Performance Standard. A quantifiable minimum level for a specified aspect of GPS SPS performance. SPS performance standards are defined in Annex A to this Signal Specification.

SPS Performance Envelope. The range of variation in specified aspects of SPS performance. Expected SPS performance characteristics are defined in Annex B to this Signal Specification.

Service Disruption. A condition over a time interval during which one or more SPS performance standards are not supported, but the civil community was warned in advance.

Major Service Failure. A condition over a time interval during which one or more SPS performance standards are not met and the civil community was not warned in advance.

1.4.2 Peformance Parameter Definitions

The definitions provided below establish the basis for correct interpretation of the GPS SPS performance standards. As was stated in Section 1.2, the GPS performance parameters contained in this Signal Specification are defined differently than other radionavigation systems in the Federal Radionavigation Plan. For a more comprehensive treatment of these definitions and their implications on system use, refer to Annex B.

Coverage. The percentage of time over a specified time 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. For the purposes of this Signal Specification, the term "near the Earth" means on or within approximately 200 kilometers of the Earth's surface.

Service Availability. Given coverage, 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.

Service Reliability. Given service availability, the percentage of time over a specified time interval that the instantaneous predictable horizontal error is maintained within a specified reliability threshold at any point on or near the Earth. Note that service reliability does not take into consideration the reliability characteristics of the SPS receiver or possible signal interference. Service reliability may be used to measure the total number of catastrophic failure hours experienced by the satellite constellation over a specified time interval.

Accuracy. Given reliable service, the percentage of time over a specified time interval that the difference between the measured and expected user position or time is within a specified tolerance at any point on or near the Earth. This general accuracy definition is further refined through the more specific definitions of four different aspects of accuracy:

- **Predictable Accuracy.** Given reliable service, the percentage of time over a specified time interval that the difference between a position measurement and a surveyed benchmark is within a specified tolerance at any point on or near the Earth.

- **Repeatable Accuracy.** Given reliable service, the percentage of time over a specified time interval that the difference between a position measurement taken at one time and a position measurement taken at another time at the same location is within a specified tolerance at any point on or near the Earth.

- **Relative Accuracy.** Given reliable service, the percentage of time over a specified time interval that the difference between two receivers' position estimates taken at the same time is within a specified tolerance at any point on or near the Earth.

- **Time Transfer Accuracy.** Given reliable service, the percentage of time over a specified time interval that the difference between a Universal Coordinated Time (commonly referred to as UTC) time estimate from the position solution and UTC as it is managed by the United States Naval Observatory (USNO) is within a specified tolerance.

1.5 Global Positioning System Overview

Sufficient information is provided below to promote a common understanding of the minimum GPS baseline configuration. The GPS baseline system is comprised of two segments, whose purpose is to provide a reliable and continuous positioning and timing service to the GPS user community. These two segments are known as the Space Segment and the Control Segment.

1.5.1 The GPS Space Segment

The GPS Block II/IIA satellite constellation normally consists of 24 operational satellites.* The Block II satellite and a slightly modified version, the Block IIA satellite, will be the mainstays of the constellation over the next decade. From a civil user's perspective, the Block II and Block IIA satellites provide an identical service. Each satellite generates a navigation message based upon data periodically uploaded from the Control Segment and adds the message to a 1.023 MHz Pseudo Random Noise (PRN) Coarse/Acquisition (C/A) code sequence. The satellite modulates the resulting code sequence onto a 1575.42 MHz L-band carrier to create a spread spectrum ranging signal, which it then broadcasts to the user community. This broadcast is referred to in this Signal Specification as the SPS ranging signal. Each C/A code is unique, and provides the mechanism to identify each satellite in the constellation. A block diagram illustrating the satellite's SPS ranging signal generation process is provided in Figure 1-1.

The Block II satellite is designed to provide reliable service over a 7.5 year design life through a combination of space qualified components, multiple redundancies for critical subsystems, and internal diagnostic logic. The Block II satellite design requires minimal interaction with the ground and allows all but a few maintenance activities to be conducted without interruption to the ranging signal broadcast. Periodic uploads of data to support navigation message generation are designed to cause no disruption to the SPS ranging signal.

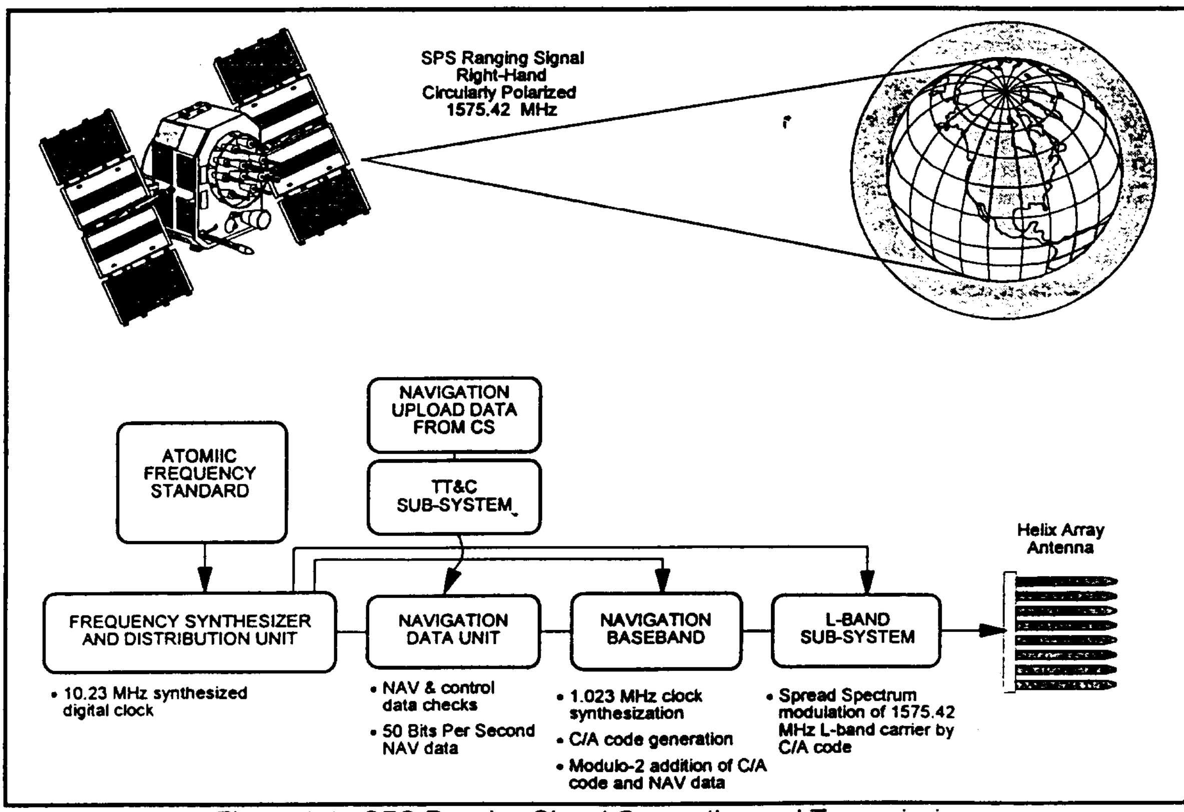


Figure 1-1. SPS Ranging Signal Generation and Transmission

* There may be some Block I satellites in the constellation, as long as they remain operable.

1.5.2 The GPS Control Segment

The GPS Control Segment (CS) is comprised of three major components: a Master Control Station (MCS), ground antennas, and monitor stations. An overview of the CS is provided in Figure 1-2.

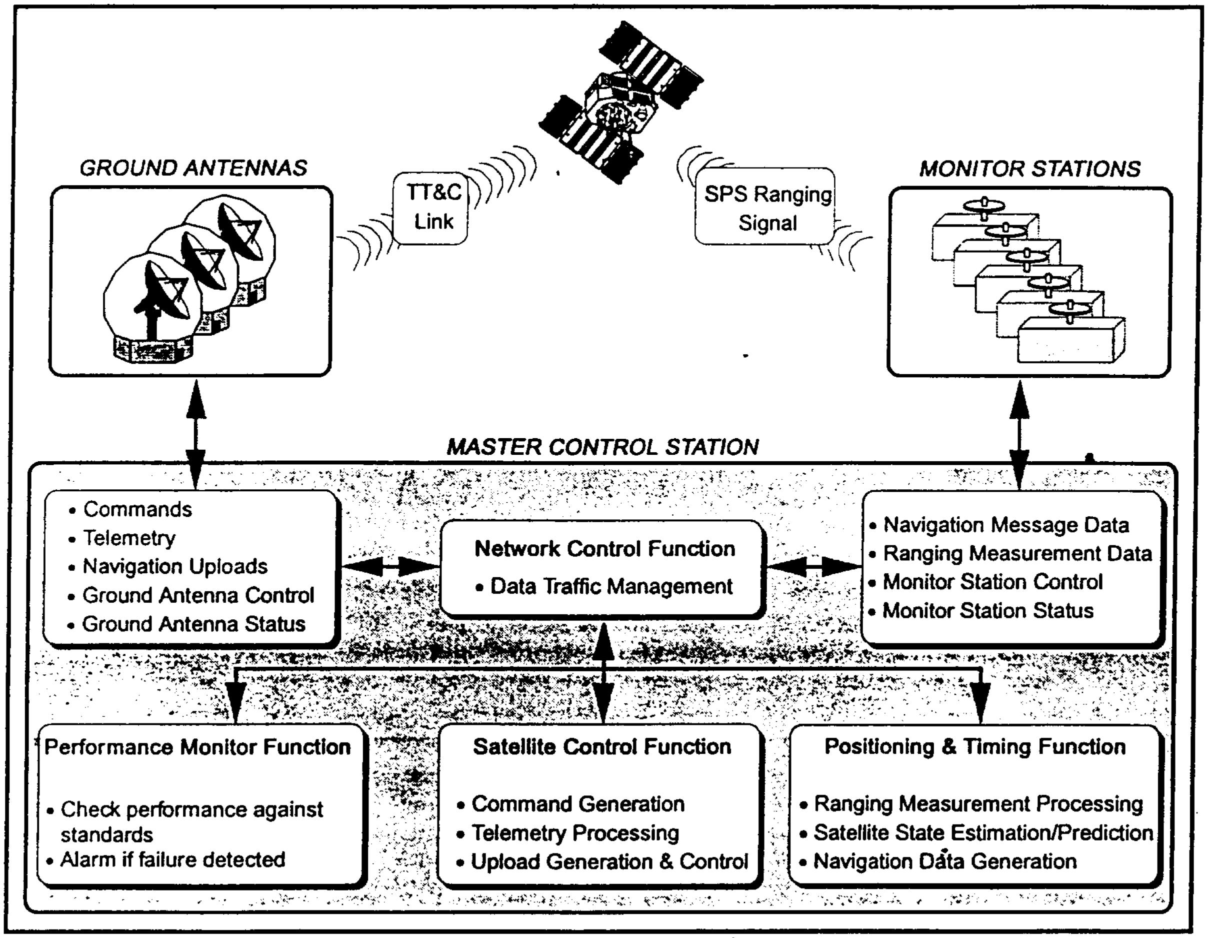


Figure 1-2. The GPS Control Segment

The MCS is located at Falcon Air Force Base, Colorado, and is the central control node for the GPS satellite constellation. Operations are maintained 24 hours a day, seven days a week throughout each year. The MCS is responsible for all aspects of constellation command and control, to include:

- Routine satellite bus and payload status monitoring.
- Satellite maintenance and anomaly resolution.
- Monitoring and management of SPS performance in support of all performance standards.
- Navigation data upload operations as required to sustain performance in accordance with accuracy performance standards.
- Prompt detection and response to service failures.

The CS's three ground antennas provide a near real-time Telemetry, Tracking and Commanding (TT&C) interface between the GPS satellites and the MCS. The five monitor stations provide near real-time satellite ranging measurement data to the MCS and support near-continuous monitoring of constellation performance.*

* Approximately 92% global coverage with all monitor stations operational.

SECTION 2.0 Specification of SPS Ranging Signal Characteristics

This section defines the SPS ranging signal and specifies its functional characteristics. The SPS receiver must be capable of receiving and processing the GPS ranging signal in accordance with the requirements provided in this Signal Specification as a prerequisite to the receiver supporting minimum SPS performance standards.

The section begins with an overview of the SPS ranging signal. The SPS signal is then specified in terms of minimum usage conditions, Radio Frequency (RF) characteristics, the navigation message data structure, and user algorithms necessary to correctly interpret and apply the navigation data.

2.1 An Overview of SPS Ranging Signal Characteristics

This section provides an overview of SPS ranging signal characteristics. SPS ranging signal characteristics are allocated to two categories: carrier and modulation RF characteristics, and the structure, protocols and contents of the navigation message.

2.1.1 An Overview of SPS Ranging Signal RF Characteristics

The GPS satellite transmits a Right Hand Circularly Polarized (RHCP) L-band signal known as L1 at 1575.42 MHz. This signal is transmitted with enough power to ensure a minimum signal power level of -160 dBw at the Earth's surface. The SPS signal generation and transmission process is represented in Figure 1-1, in Section 1.5.

L1 is Bipolar-Phase Shift Key (BPSK) modulated with a Pseudo Random Noise (PRN) 1.023 MHz code known as the Coarse/Acquisition (C/A) code. This C/A code sequence repeats each millisecond. The transmitted PRN code sequence is actually the Modulo-2 addition of a 50 Hz navigation message and the C/A code. The SPS receiver demodulates the received code from the L1 carrier, and detects the differences between the transmitted and the receiver-generated code. The SPS receiver uses an exclusive-or truth table to reconstruct the navigation data, based upon the detected differences in the two codes.

2.1.2 An Overview of the GPS Navigation Message

Each GPS satellite provides data required to support the position determination process. Figure 2-1 provides an overview of the data contents and structure within the navigation message. The data includes information required to determine the following:

- Satellite time of transmission
- Satellite position
- Satellite health
- Satellite clock correction
- Propagation delay effects
- Time transfer to UTC
- Constellation status

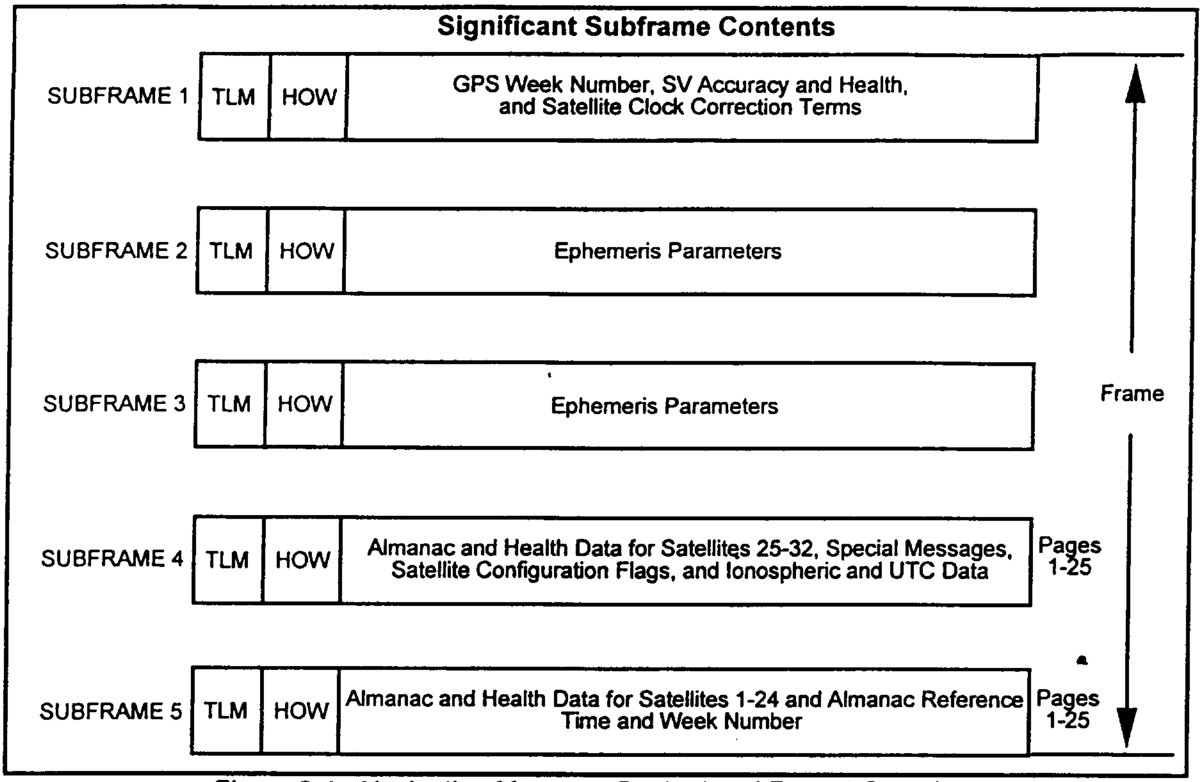


Figure 2-1. Navigation Message Content and Format Overview

2.2 Minimum Usage Conditions

Although the DOD specifies and controls the characteristics and performance of the GPS ranging signals, SPS performance must be specified in the positioning domain. However, since the definition of SPS receiver design requirements is not within the scope of this document, certain minimum assumptions concerning receiver design and usage must be made in order to map ranging signal performance characteristics into the positioning domain. These assumptions establish the minimum position and time determination capabilities which an SPS receiver must possess to meet the minimum performance standards, as they are specified in Annex A. Users whose receiver designs do not meet these assumptions may not experience performance in accordance with the performance standards.

2.2.1 Satellite Tracking and Selection

The SPS receiver must provide the capability to track and generate a position solution based upon measurements and data taken from at least four satellites. No other assumptions are made regarding the SPS receiver's channel architecture or ranging signal measurement strategy.

The SPS receiver must be capable of tracking and using satellites down to a 5° mask angle with respect to the local horizon. The local horizon is defined for the purposes of this Signal Specification to be equivalent to the local tangent plane, with respect to the ellipsoid model used in the position solution. Performance standards do not take into consideration the presence of obscura above the 5° mask angle.

The SPS receiver must be able to compensate for dynamic Doppler shift effects on nominal SPS ranging signal carrier phase and C/A code measurements. The SPS receiver manufacturer is responsible for ensuring that the receiver compensates for Doppler shift behavior unique to the receiver's anticipated application. Doppler shift behavior is a function of expected satellite-to-user relative velocities, where the primary uncertainty is the dynamics of the user platform.

Satellite selection must be based upon the minimum Position Dilution of Precision (PDOP). The performance standard definitions are based upon an assumption that the SPS receiver will re-compute the optimum PDOP every five minutes, or whenever a satellite used in the position solution sets below the 5° mask angle.

The SPS receiver must have the capability to read the health field and status bits in the navigation message, and exclude unhealthy satellites from the position solution.

Each time the SPS receiver is powered on, it must ensure that it is using up-to-date ephemeris and clock data for the satellites it is using in its position solution. The SPS receiver designer is encouraged to monitor the Issue of Data, Clock (IODC)/Issue of Data, Ephemeris (IODE) values, and to update ephemeris and clock data based upon a detected change in one or both of these values. At a minimum, the SPS receiver must update its ephemeris and clock data for a given satellite no more than two hours after it last updated its data for that satellite. The SPS receiver must ensure that the datasets it uses in the position solution process are internally consistent for a given satellite, and are not mixes of old and new data.

A satellite broadcasting a User Range Accuracy (URA) value in excess of 32 meters is not considered to be operating within the SPS performance standards. SPS receivers which use satellites with URAs exceeding 32 meters may not experience performance in accordance with the standards.

2.2.2 SPS Receiver Design and Usage Contributions to Position Solution Error

The SPS receiver's error contribution to the SPS ranging error is not taken into consideration in the definition of SPS performance standards. SPS accuracy standards reflect only the error characteristics of the signal-in-space.

Atmospheric propagation path effects on single-frequency range measurement accuracy are taken into consideration in the accuracy performance standard development. The accuracy performance standard development assumes that the SPS receiver design implements the satellite position estimate, measured range computation, ionospheric correction, and satellite time correction algorithms in accordance with this Signal Specification. The performance standards do not consider the possible effects of multipath on position solution accuracy, other than the specification of a 5° mask angle.

Platform dynamics are not explicitly taken into consideration in performance standard development. However, receivers that are designed to operate under medium dynamic conditions should not experience degradations in service availability or accuracy. The term *medium dynamic conditions* is defined here to mean SPS user motion which does not: 1) impart acceleration or jerk effects on frequency, phase or code measurements in excess of those experienced by a stationary user, or 2) change the receiver antenna's nominal orientation with respect to local horizontal.

The SPS receiver must implement the Universal Coordinated Time (UTC) corrections supplied in the navigation message, in order to experience position solution time transfer accuracies as specified in the accuracy performance standard.

2.2.3 Position Fix Dimensions

The GPS architecture provides the inherent capability to solve for a four-dimensional solution. The specific coordinate system used to define the position solution's output dimensions will be unique to a given SPS receiver's design and user's needs. However, GPS operates in a well-defined set of coordinate systems, and all performance standard definitions assume their usage. The satellite position and geometric range computations must be accomplished in the World Geodetic Survey 1984 (WGS-84) Earth-Centered, Earth-Fixed (ECEF) coordinate system. In order for the user to experience performance consistent with the performance standards, the position solution must be accomplished in WGS-84 local coordinates, or in a local coordinate system which meets the following conditions:

- The coordinate system must have an accepted mathematical relationship with the WGS-84 ECEF coordinate system.
- Latitude must be defined with respect to the equator of a documented ellipsoid model.
- Longitude must be defined with respect to the Greenwich meridian, or another reference that has a documented relationship with the Greenwich meridian.
- Local horizontal must be defined as a plane perpendicular to a documented ellipsoid model's local radius of curvature, or tangent to the ellipsoid surface at the user's location.
- Local vertical must be defined to be parallel with a documented ellipsoid model's local radius of curvature, or perpendicular to the local horizontal plane.

2.2.4 Position Fix Rate

SPS accuracy measurement algorithms (defined in Annex C) are based upon a position fix rate of once per second, to support high confidence interval evaluations. However, the use of different fix rates is not precluded in the performance standard definition, since the instantaneous position solution predictable error is independent of the fix rate.

2.2.5 Position Solution Ambiguity

SPS performance standards (as specified in Annex A) assume no ambiguities in the position solution process. The formal derivation of the GPS position solution does however admit the possibility of position determination ambiguities due to bifurcate solutions, although the probability is nil for users on or near the surface of the Earth. The potential for ambiguity arises from the occurrence of very specific and rare conditions in the position solution geometry. The probability of an ambiguity occurring is completely dependent on how the receiver manufacturer's position solution implementation deals with bifurcate solution conditions.

2.3 SPS Ranging Signal RF Characteristics

This section specifies the functional characteristics of the SPS L-band carrier and the C/A code.

2.3.1 Ranging Signal Carrier Characteristics

The L-band carrier is modulated by a bit train which is a composite generated by the Modulo-2 addition of a Pseudo Random Noise (PRN) ranging code and downlink system data (referred to as navigation data or the navigation message).

2.3.1.1 Frequency Plan

The L-band SPS ranging signal is contained within a 2.046 MHz band centered about L1. The carrier frequency for the L1 signal is coherently derived from a frequency source within the satellite. The nominal frequency of this source -- as it appears to an observer on the ground -- is 1.023 MHz. To compensate for relativistic effects, the output frequency of the satellite's frequency standard -- as it would appear to an observer located at the satellite -- is 10.23 MHz offset by a $\Delta f/f = -4.4647 \times 10^{-18}$ or a $\Delta f = -4.567 \times 10^{-3}$ Hz. This frequency offset results in an output of 10.22999999543 MHz, which is frequency divided to obtain the appropriate carrier modulation signal (1.022999999543 MHz). The same output frequency source is also used to generate the nominal L1 carrier frequency (f_0) of 1575.42 MHz.

2.3.1.2 Correlation Loss

Correlation loss is defined as the difference between the satellite power received in a 2.046 MHz bandwidth and the signal power recovered in an nominal correlation receiver of the same bandwidth. On the L1 channel, the correlation loss apportionment is as follows:

- Satellite modulation imperfections 0.6 dB
- Ideal user receiver waveform distortion 0.4 dB

2.3.1.3 Carrier Phase Noise

The phase noise spectral density of the unmodulated carrier is such that a phase locked loop of 10 Hz one-sided noise bandwidth is able to track the carrier to an accuracy of 0.1 radians RMS.

2.3.1.4 Spurious Transmissions

In-band spurious transmissions are at least 40 dB below the unmodulated L1 carrier over the allocated channel bandwidth.

2.3.1.5 Equipment Group Delay

Equipment group delay is defined as the delay between the L-band radiated output of a specific satellite (measured at the antenna phase center) and the output of that satellite's on-board frequency source; the delay consists of a bias term and an uncertainty. The bias term is of minimal concern to the SPS user since the majority of its value is included in clock correction parameters relayed in the navigation data, and is therefore accounted for by the user computations of system time (reference paragraph 2.5.5.2). The SPS receiver manufacturer and user should note that a C/A code epoch may vary up to 10 nanoseconds (2σ) with respect to the clock correction parameters provided in the navigation message.

2.3.1.6 Signal Polarization

The transmitted signal is right-hand circularly polarized. The ellipticity for L1 will not exceed 1.2 dB for the angular range of ±14.3 degrees from boresight.

2.3.2 C/A Code Generation and Timing

The SPS PRN ranging code is known as the Coarse/Acquisition (C/A) code. Appropriate code-division-multiplexing techniques allow differentiating between the satellites even though they all transmit on the same L-band frequency.

The characteristics of the C/A code are defined below in terms of its structure and the basic method used for generating it. The C/A code consists of 1.023 Mbps $G_i(t)$ patterns with Modulo 2 addition of the navigation data bit train, D(t), which is clocked at 50 bps. The resultant composite bit train is then used to BPSK modulate the L-band carrier. The user receiver is then required to independently generate and synchronize with the satellite transmitted C/A code and perform Modulo 2 addition in order to decode and interpret the navigation message.

2.3.2.1 C/A Code Structure

The linear $G_i(t)$ pattern (C/A-code) is the Modulo-2 sum of two 1023-bit linear patterns, G1 and $G2_i$. The latter sequence is selectively delayed by an integer number of chips to produce 36 unique G(t) patterns (defined in Table 2-1). This allows the generation of 36 unique C/A(t) code phases using the same basic code generator. The G1 and G2 shift register generator configurations are represented in Figures 2-2 and 2-3, respectively.

2.3.2.2 C/A-Code Generation

Each $G_i(t)$ sequence is a 1023-bit Gold-code which is itself the Modulo-2 sum of two 1023-bit linear patterns, G1 and $G2_i$. The $G2_i$ sequence is formed by effectively delaying the G2 sequence by an integer number of chips ranging from 5 to 950. The G1 and G2 sequences are generated by 10-stage shift registers having the following polynomials as referred to in the shift register input (see Figures 2-4 and 2-5).

G1: $X^{10} + X^3 + 1$, and

G2: $X^{10} + X^9 + X^8 + X^6 + X^3 + X^2 + 1$.

The initialization vector for the G1 and G2 sequences is (1111111111). The G1 and G2 registers are clocked at a 1.023 MHz rate. The effective delay of the G2 sequence to form the $G2_i$ sequence is accomplished by combining the output of two stages of the G2 shift register by Modulo-2 addition (see Figure 2-4). Thirty-six of the possible combinations are selected. Table 2-1 contains a tabulation of the G2 shift register taps selected and their corresponding PRN signal numbers together with the first several chips of each resultant PRN code. Timing relationships related to the C/A code are shown in Figure 2-5.

2.3.2.3 Non-Standard Code

An operational GPS satellite will transmit an intentionally "incorrect" version of the C/A code where needed to protect the users from receiving and utilizing an anomalous navigation signal. This "incorrect" code is termed the non-standard C/A (NSC) code. A satellite will transition to NSC as a result of an autonomously detected malfunction in the satellite's navigation payload. Since the NSC is designed to protect the user, it is not for utilization by the user and, therefore, is not defined in this document. Note that Block I satellites do not have NSC capability.

2.3.3 Code Modulation and Signal Transmission

2.3.3.1 Navigation Data

The navigation data, D(t), includes satellite ephemerides, system time, correction data, satellite clock behavior data, status messages, etc. The 50 bps data is Modulo-2 added to the C/A code.

2.3.3.2 L-Band Signal Structure

The SPS L1 carrier is Bipolar-Phase Shift Key (BPSK) modulated by the composite C/A code/navigation data bit train. For a particular satellite, all transmitted signal elements (carrier, code, and data) are coherently derived from the same on-board frequency source.

Table 2-1. Code Phase Assignments

Satellite ID Number	GPS PRN Signal Number	Code Phase Selection	Code Delay Chips	First 10 Chips Octal*
		C/A ($G2_i$)	C/A	C/A
1	1	2 ⊕ 6	5	1440
2	2	3 ⊕ 7	6	1620
3	3	4 ⊕ 8	7	1710
4	4	5 ⊕ 9	8	1744
5	5	1 ⊕ 9	17	1133
6	6	2 ⊕ 10	18	1455
7	7	1 ⊕ 8	139	1131
8	8	2 ⊕ 9	140	1454
9	9	3 ⊕ 10	141	1626
10	10	2 ⊕ 3	251	1504
11	11	3 ⊕ 4	252	1642
12	12	5 ⊕ 6	254	1750
13	13	6 ⊕ 7	255	1764
14	14	7 ⊕ 8	256	1772
15	15	8 ⊕ 9	257	1775
16	16	9 ⊕ 10	258	1776
17	17	1 ⊕ 4	469	1156
18	18	2 ⊕ 5	470	1467
19	19	3 ⊕ 6	471	1633
20	20	4 ⊕ 7	472	1715
21	21	5 ⊕ 8	473	1746
22	22	6 ⊕ 9	474	1763
23	23	1 ⊕ 3	509	1063
24	24	4 ⊕ 6	512	1706
25	25	5 ⊕ 7	513	1743
26	26	6 ⊕ 8	514	1761
27	27	7 ⊕ 9	515	1770
28	28	8 ⊕ 10	516	1774
29	29	1 ⊕ 6	859	1127
30	30	2 ⊕ 7	860	1453
31	31	3 ⊕ 8	861	1625
32	32	4 ⊕ 9	862	1712
***	33	5 ⊕ 10	863	1745
***	34**	4 ⊕ 10	950	1713
***	35	1 ⊕ 7	947	1134
***	36	2 ⊕ 8	948	1456
***	37**	4 ⊕ 10	950	1713

* In the octal notation for the first 10 chips of the C/A code as shown in this column, the first digit (1) represents a "1" for the first chip and the last three digits are the conventional octal representation of the remaining 9 chips. (For example, the first 10 chips of the C/A code for PRN Signal Assembly No. 1 are: 1100100000).

** C/A codes 34 and 37 are common.

*** PRN sequences 33 through 37 are reserved for other uses (e.g. ground transmitters).

⊕ = "exclusive or"

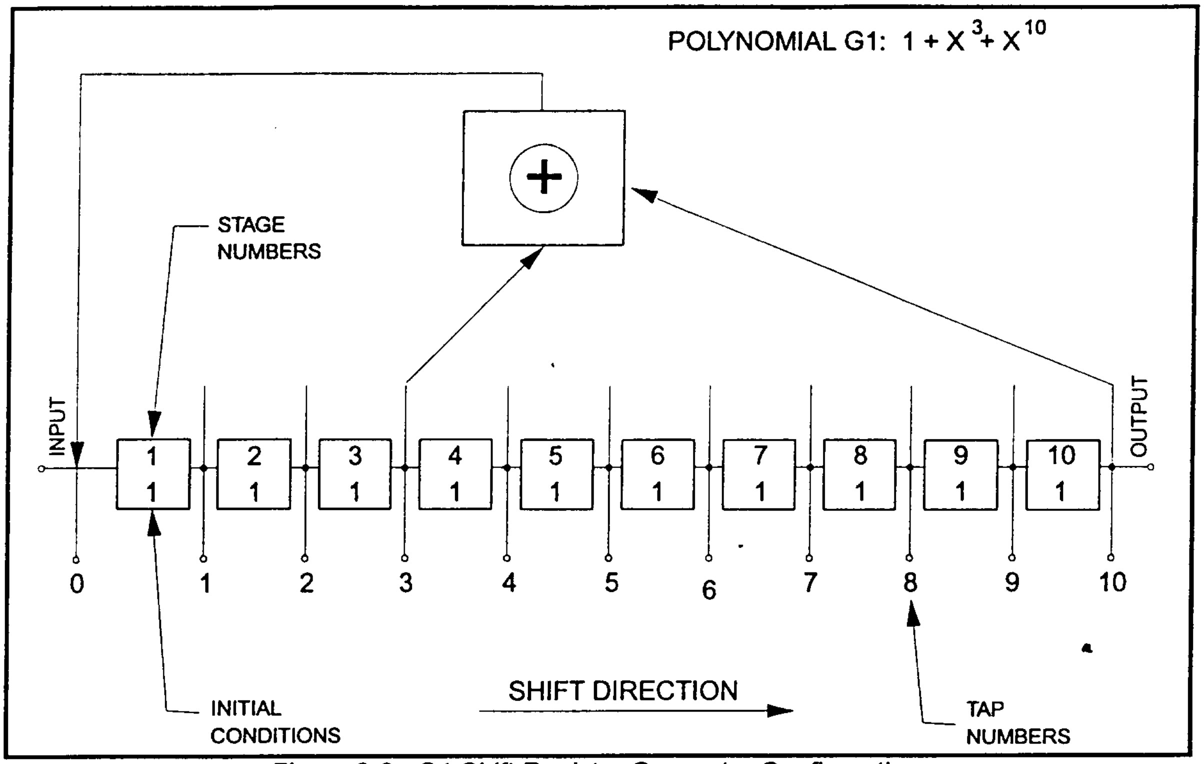


Figure 2-2. G1 Shift Register Generator Configuration

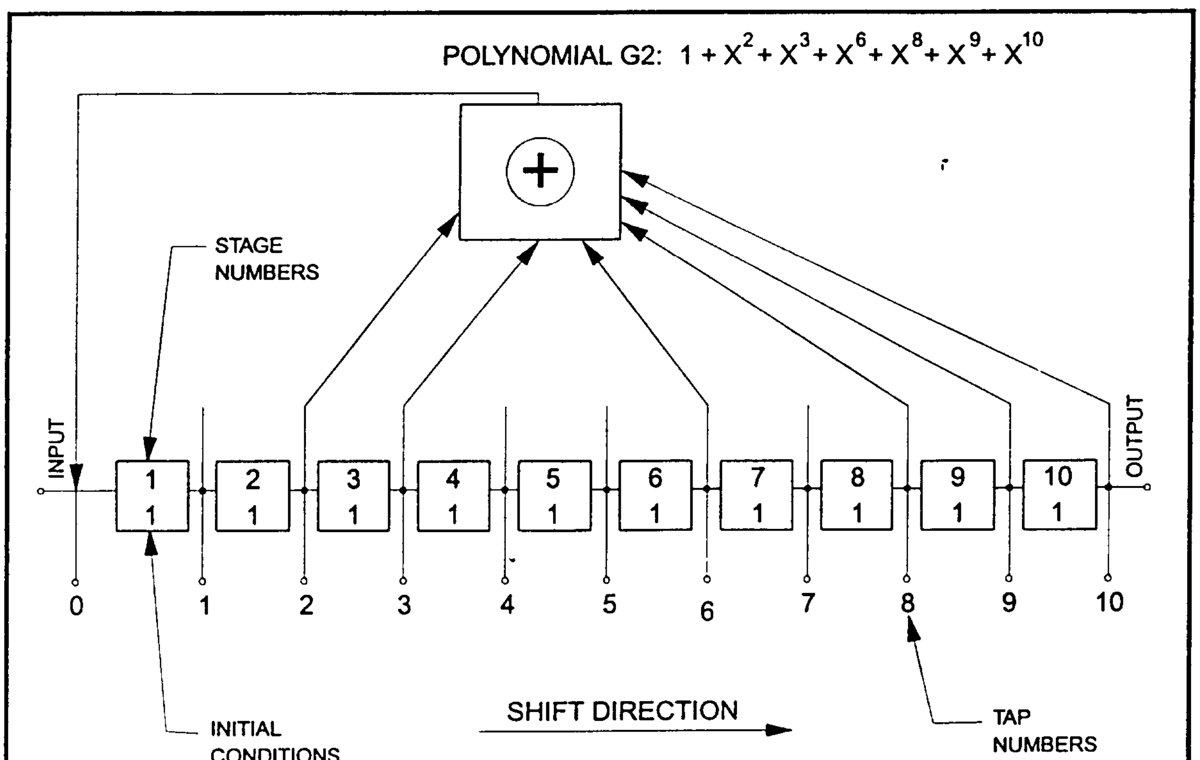


Figure 2-3. G2 Shift Register Generator Configuration

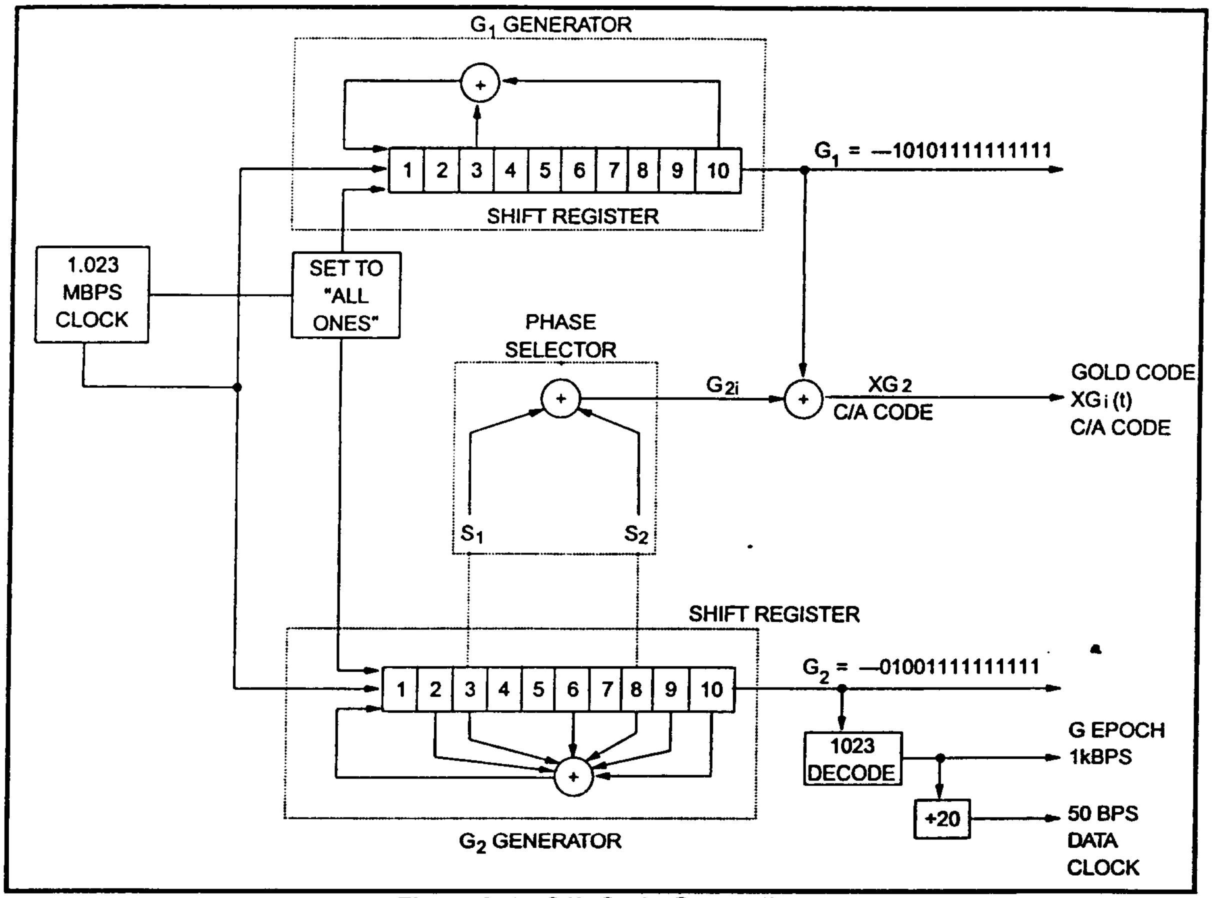


Figure 2-4. C/A-Code Generation

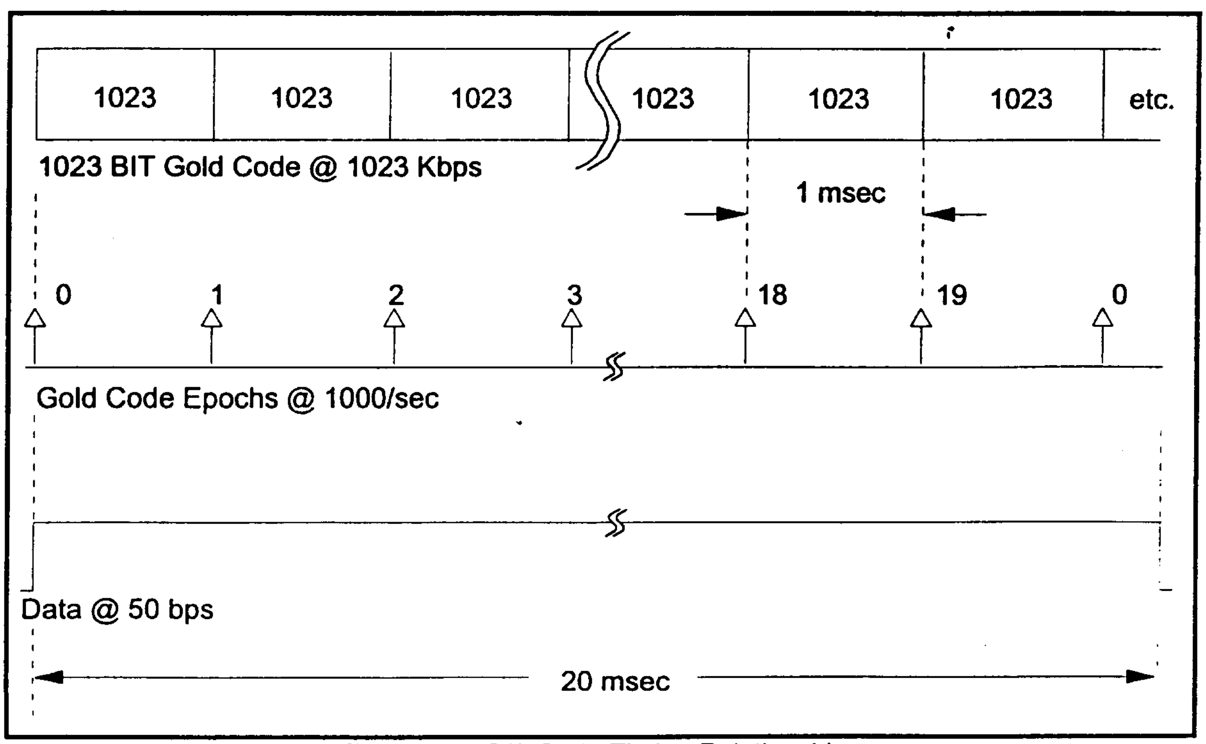


Figure 2-5. C/A Code Timing Relationships

2.3.4 Signal Coverage and Power Distribution

Figure 2-6 illustrates the minimum power of the near-ground user-received L1 signal as a function of satellite elevation angle using the following assumptions: (a) the signal is measured at the output of a 3 dBi linear polarized receiving antenna, (b) the satellite is at or above a 5 degree elevation angle, (c) the received signal levels are observed within the in-band allocation defined in paragraph 2.1.1, (d) the atmospheric path loss is 2.0 dB, and (e) the satellite attitude error is 0.5 degrees (towards reducing signal level).

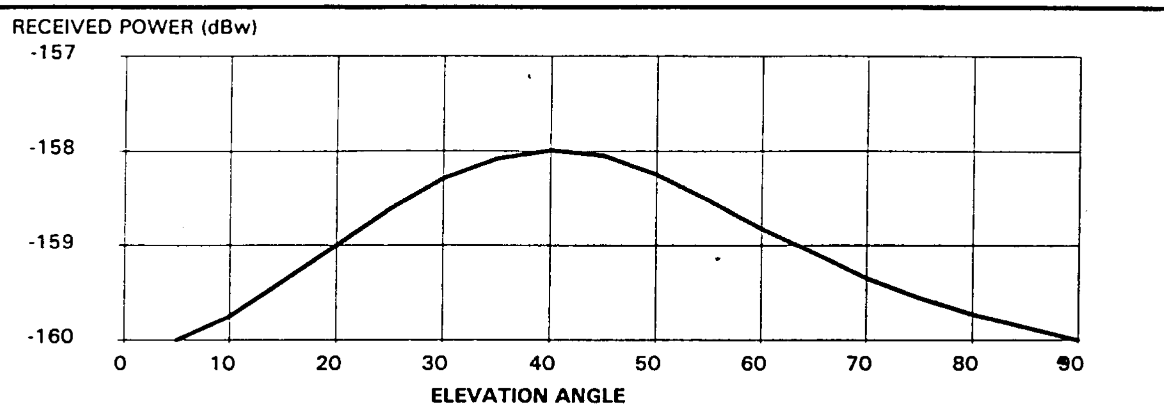


Figure 2-6. User Received Minimum Signal Levels

Higher received signal levels can be caused by such factors as satellite attitude errors, mechanical antenna alignment errors, transmitter power output variations due to temperature variations, voltage variations and power amplifier variations, and due to a variability in link atmospheric path loss. The maximum received L1 C/A signal levels as a result of these factors is not expected to exceed -153.0 dBw. This estimate assumes that the receiving antenna characteristics are as described above, the atmospheric loss is 0.6 dB and the satellite attitude error is 0.5 degrees (towards increased signal level).

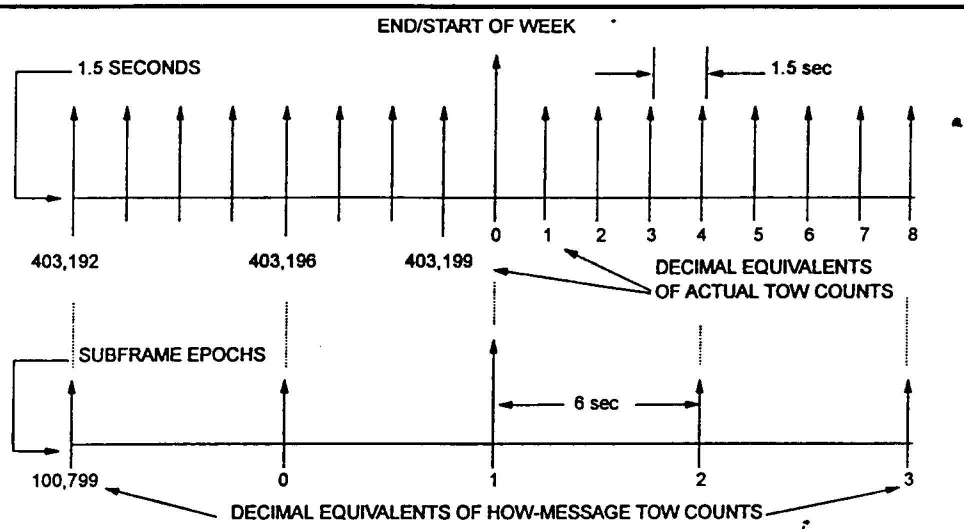
2.3.5 GPS Time and the Satellite Z-Count

GPS time is established by the Control Segment and is used as the primary time reference for all GPS operations. GPS time is referenced to a UTC (as maintained by the U.S. Naval Observatory) zero time-point defined as midnight on the night of January 5, 1980/morning of January 6, 1980. The largest unit used in stating GPS time is one week, defined as 604,800 seconds. GPS time may differ from UTC because GPS time is a continuous time scale, while UTC is corrected periodically with an integer number of leap seconds. There also is an inherent but bounded drift rate between the UTC and GPS time scales. The GPS time scale is maintained to be within one microsecond of UTC (Modulo one second). The navigation data contains the requisite data for relating GPS time to UTC.

In each satellite, an internally derived 1.5 second epoch provides a convenient unit for precisely counting and communicating time. Time stated in this manner is referred to as a Z-count. The Z-count is provided to the user as a 29-bit binary number consisting of two parts as follows:

a. The binary number represented by the 19 least significant bits of the Z-count is referred to as the time of week (TOW) count and is defined as being equal to the number of 1.5 second epochs that have occurred since the transition from the previous week. The count is short-cycled such that the range of the TOW-count is from 0 to 403,199 1.5 second epochs (equaling one week) and is reset to zero at the end of each week. The TOW-count's zero state is defined as that 1.5 second epoch which is coincident with the start of the present week. This epoch occurs at (approximately) midnight Saturday night-Sunday morning, where midnight is defined as 0000 hours on the Universal Coordinated Time (UTC) scale which is nominally referenced to the Greenwich Meridian. Over the years, the occurrence of the "zero state epoch" may differ by a few seconds from 0000 hours on the UTC scale, since UTC is periodically corrected with leap seconds while the TOW-count is continuous without such correction. A truncated version of the TOW-count, consisting of its 17 most significant bits, is contained in the hand-over word (HOW) of the L-Band downlink data stream; the relationship between the actual TOW-count and its truncated HOW version is illustrated by Figure 2-7.

b. The ten most significant bits of the Z-count are a binary representation of the sequential number assigned to the present GPS week (Modulo 1024). The range of this count is from 0 to 1023, with its zero state being defined as that week which starts with the 1.5 second epoch occurring at (approximately) midnight on the night of January 5, 1980/morning of January 6, 1980. At the expiration of GPS week number 1023, the GPS week number will rollover to zero (0). Users must account for the previous 1024 weeks in conversions from GPS time to a calendar date.



NOTE:
1. TO AID IN RAPID GROUND LOCK-ON THE HAND-OVER WORD (HOW) OF EACH SUBFRAME CONTAINS A TRUNCATED TIME-OF-WEEK (TOW) COUNT.
2. THE HOW IS THE SECOND WORD IN EACH SUBFRAME.
3. THE HOW-MESSAGE TOW COUNT CONSISTS OF THE 17 MSB's OF THE ACTUAL TOW COUNT AT THE START OF THE NEXT SUBFRAME.
4. TO CONVERT FROM THE HOW-MESSAGE TOW COUNT TO THE ACTUAL TOW COUNT AT THE START OF THE NEXT SUBFRAME, MULTIPLY BY FOUR.
5. THE FIRST SUBFRAME STARTS SYNCHRONOUSLY WITH THE END/START OF WEEK EPOCH.

Figure 2-7. Time Line Relationship of HOW Word

2.4 Navigation Message Data Structure

2.4.1 Message Structure

The navigation message is transmitted by the satellite on the L1 data link at a rate of 50 bps. The following sections define the navigation data format and contents. Implementation algorithms for this data are provided in Section 2.5.

2.4.1.1 Data Page Format

As shown in Figure 2-8, the message structure utilizes a basic format of a 1500 bit long frame made up of five subframes, each subframe being 300 bits long. Subframes 4 and 5 are subcommutated 25 times each, so that a complete data message will require the transmission of 25 full frames. The 25 versions of subframes 4 and 5 are referred to as pages 1 through 25 of each subframe. Each subframe will consist of ten words, each 30 bits long; the MSB of all words is transmitted first.

Each subframe and/or page of a subframe starts with a Telemetry (TLM) word and a Handover word (HOW) pair. The TLM word is transmitted first, immediately followed by the HOW. The latter is followed by eight data words. Each word in each frame contains parity.

At end/start of week (a) the cyclic paging to subframes 1 through 5 will restart with subframe 1 regardless of which subframe was last transmitted prior to end/start of week, and (b) the cycling of the 25 pages of subframes 4 and 5 will restart with page 1 of each of the subframes, regardless of which page was the last to be transmitted prior to the end/start of week. All upload and page cutovers will occur on frame boundaries (i.e., Modulo 30 seconds relative to end/start of week); accordingly, new data in subframes 4 and 5 may start to be transmitted with any of the 25 pages of these subframes.

2.4.1.2 Data Parity

Words one through ten of subframes 1-5 each contain six parity bits as their LSBs. In addition, two non-information bearing bits are provided as bits 23 and 24 of words two and ten for parity computation purposes. The algorithm provided to the user to properly compute parity is listed in Section 2.5.2.

2.4.2 Telemetry and Handover Words

The format and contents of the Telemetry (TLM) word and the Handover Word (HOW) are described in the following subparagraphs. Figure 2-9 provides a definition of TLM word and HOW formats.

2.4.2.1 Telemetry Word

Each TLM word is 30 bits long, occurs every six seconds in the data frame, and is the first word in each subframe/page. The format is as shown in Figure 2-9. Bit 1 is transmitted first. Each TLM word begins with a preamble, followed by 16 reserved bits and six parity bits.

2.4.2.2 Handover Word

The HOW is 30 bits long and is the second word in each subframe/page, immediately following the TLM word. A HOW occurs every 6 seconds in the data frame. The format and content of the HOW is as shown in Figure 2-9. The MSB is transmitted first. The HOW begins with the 17 MSBs of the time-of-week (TOW) count. (The full TOW count consists of the 19 LSBs of the 29-bit Z-count). These 17 bits correspond to the TOW-count at the 1.5 second epoch which occurs at the start (leading edge) of the next following subframe (reference paragraph 2.3.5).

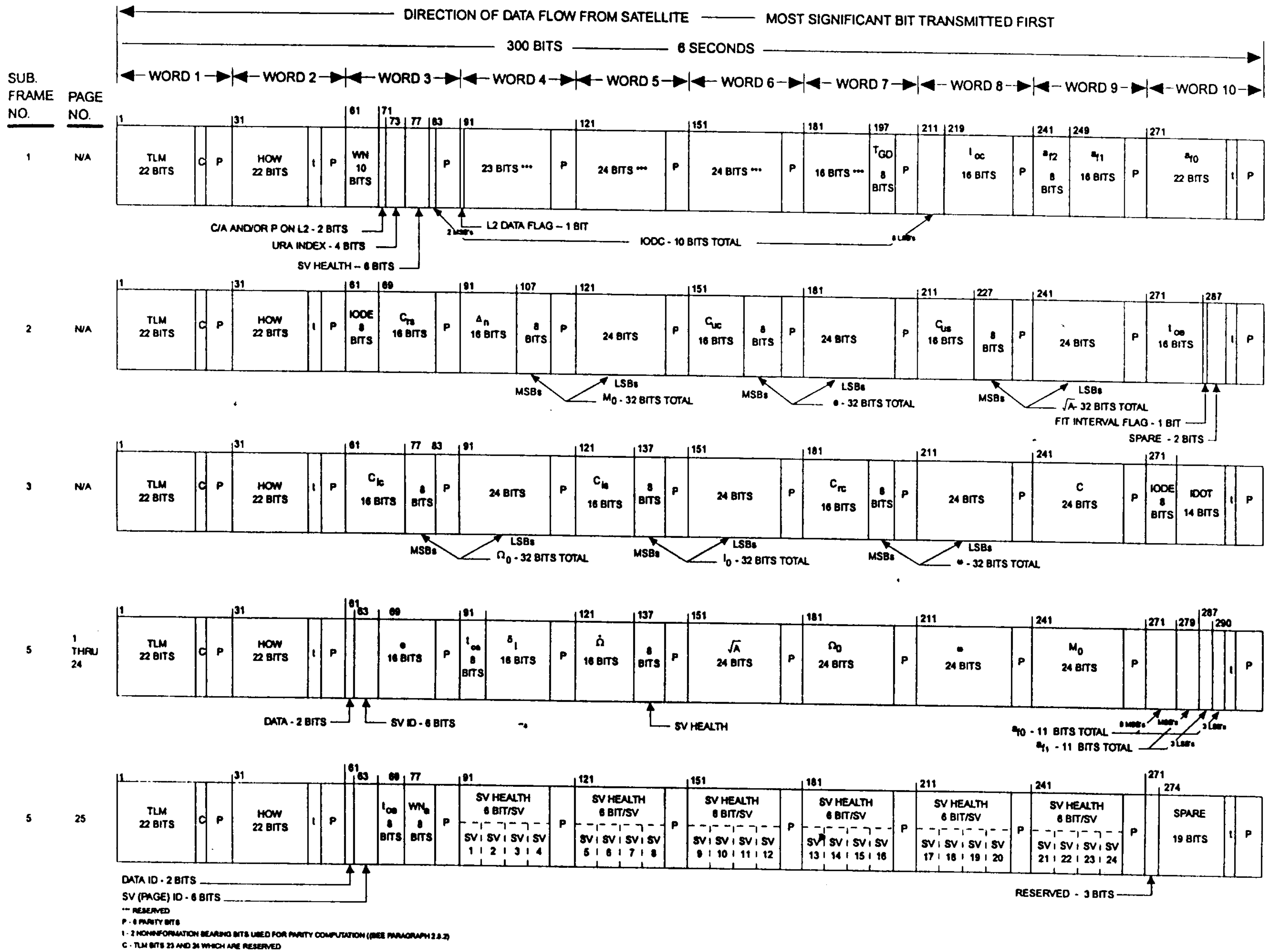
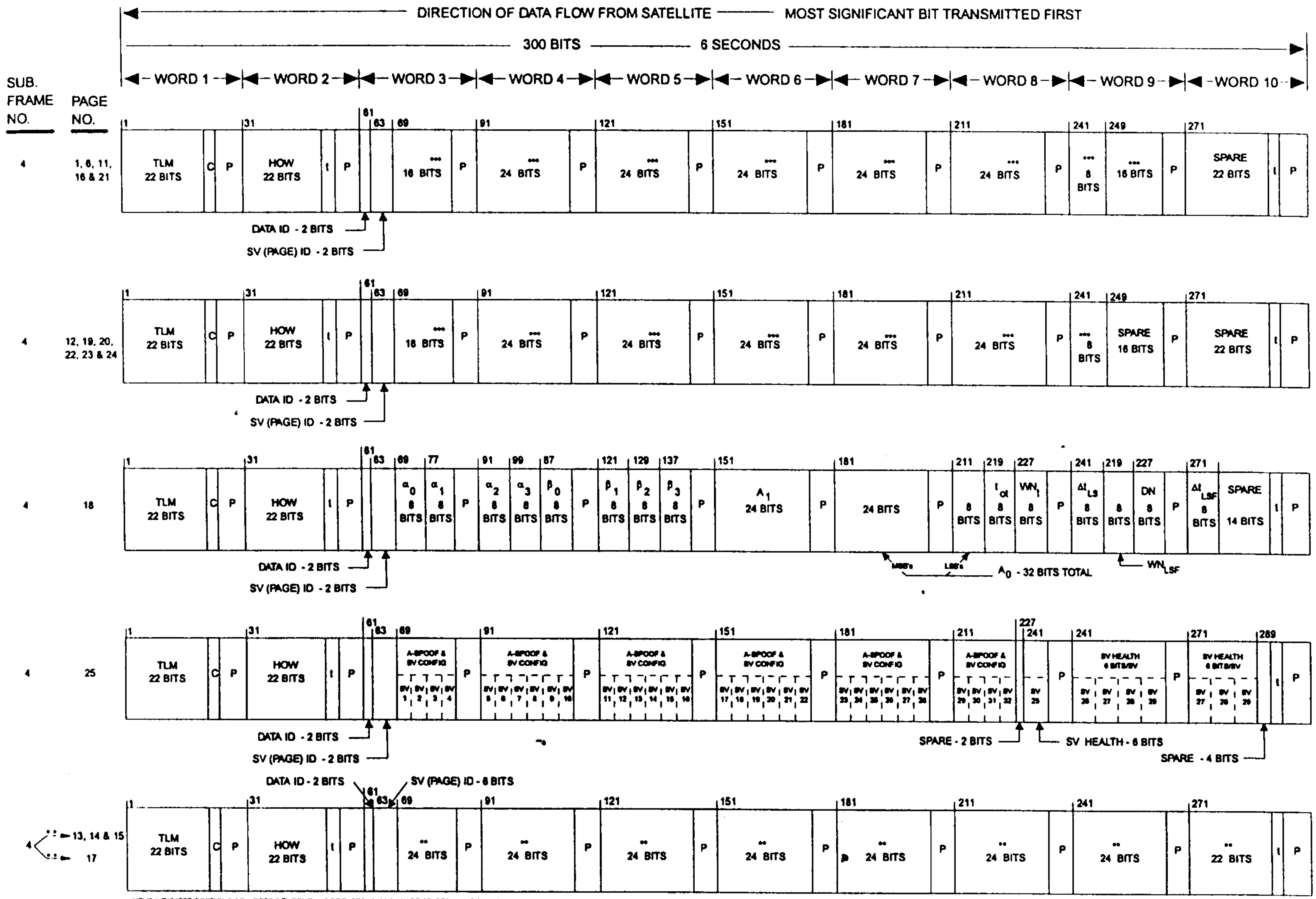


Figure 2-8. Data Format (Sheet 1 of 2)



**THE INDICATED PORTIONS OF WORDS 3 THROUGH 10 OF PAGES 13, 14 & 15 ARE SPARES WHILE THOSE OF PAGE 17 ARE RESERVED FOR SPECIAL MESSAGES (PLUS SPARES) PER PARAGRAPH 2.4.5.7

*** RESERVED

P = 6 PARITY BITS
t = 2 NONINFORMATION BEARING BITS USED FOR PARITY COMPUTATION (SEE PARAGRAPH 2.5.2)
C = TLM BITS 23 & 24 WHICH ARE RESERVED
NOTE PAGES 2,3,4,5,7,8,9 & 10 FOR SUBFRAME 4 HAVE SAME FORMAT AS PAGES 1 THOUGH 24 OF SUBFRAME 5

Figure 2-8. Data Format (Sheet 2 of 2)

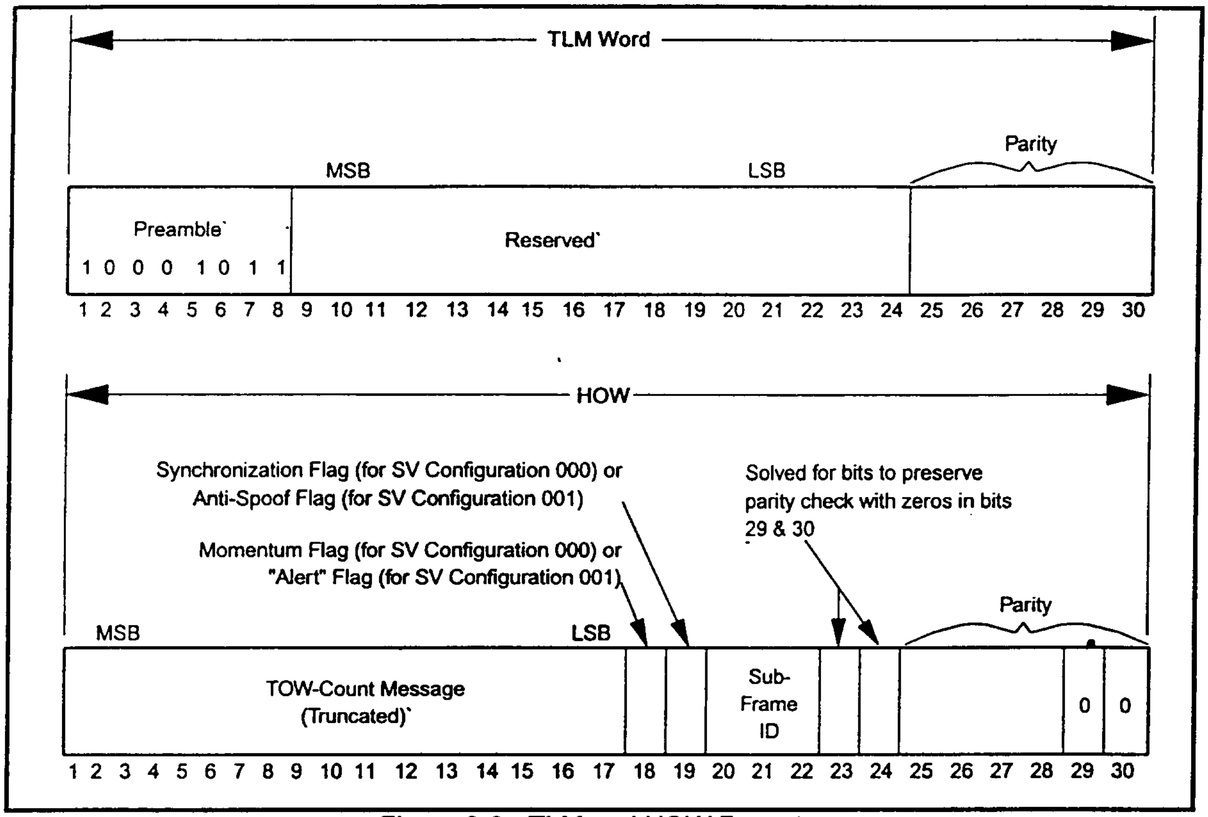


Figure 2-9. TLM and HOW Formats

Bit 18 is used in two ways: (a) on satellites that are designated by configuration code 000, bit 18 is the roll momentum dump flag with a "1" in this bit-position indicating that a non-conservative (thruster type) momentum dump has occurred since the last upload (this flag is reset at a new end-of message transmission at the conclusion of the next upload); and (b) on satellites designated by configuration code 001, bit 18 is an "alert" flag. When this flag is raised (bit 18 = "1"), it will indicate to the SPS user that the satellite URA may be worse than indicated in subframe 1 and that the user will use that satellite at the user's own risk.

Bit 19 also has a dual role: (a) on satellites that are designated by configuration code 000 in page 25 of subframe 4, bit 19 is used as a synchronization flag; and (b) on satellites designated by configuration code 001, bit 19 is an anti-spoof (A-S) flag.

When used as a synchronization flag, a "0" in bit position 19 indicates that the satellite is in synchronism, which is defined as the condition in which the leading edge of the TLM word is coincident with the 1.5 second epoch. If bit 19 is a "1", this condition may not exist; i.e., the satellite is not in synchronism, and further data from this satellite should not be used since it may be erroneous. When used as an A-S flag, a "1" in bit position 19 indicates that the A-S mode is ON in that satellite.

Bits 20, 21, and 22 of the HOW provide the ID of the subframe in which that particular HOW is the second word; the ID code is as follows:

Subframe	ID Code
1	001
2	010
3	011
4	100
5	101

2.4.3 Subframe 1 - Satellite Clock and Health Data

The content of words three through ten of subframe 1 contain the clock parameters and other data described in the following discussion. The number of bits, the scale factor of the LSB (which is the last bit received), the range, and the units are as specified in Table 2-2.

Table 2-2. Subframe 1 Parameters

Parameter	No. of Bits	Scale Factor (LSB)	Effective Range***	Units
Week No.	10	1		Week
satellite accuracy	4			(see text)
satellite health	6	1		discretes
T_{GD}	8*	2^{-31}		seconds
IODC	10			(see text)
t_{oc}	16	2^{4}	604,784	seconds
a_{f2}	8*	2^{-55}		sec/sec^2
a_{f1}	16*	2^{-43}		sec/sec
a_{f0}	22*	2^{-31}		seconds

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the MSB;
** See Figure 2-8 for complete bit allocation in subframe;
*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

The clock parameters describe the satellite time scale during the period of validity. The parameters in a data set are valid during the interval of time in which they are transmitted and will remain valid for an additional period of time after transmission of the next data set has started.

2.4.3.1 Week Number

The ten MSBs of word three contain the ten MSBs of the 29-bit Z-count as qualified herein. These ten bits represent the number of the current GPS week at the start of the data set transmission interval with "all zeros" indicating week "0". The GPS week number increments at each end/start of week epoch.

2.4.3.2 User Range Accuracy

Bits 13 through 16 of word three give the predicted User Range Accuracy (URA) of the satellite. URA is a statistical indicator of the contribution of the apparent clock and ephemeris prediction accuracies to the ranging accuracies obtainable with a specific satellite based on historical data. The URA reported in the navigation message shall correspond to the maximum value anticipated during the validity period of the transmitted data, with uniform SA levels invoked. Note that the URA does not include error estimates due to inaccuracies of the single-frequency ionospheric delay model.

2.4.3.3 Satellite Health

The six-bit health indication given by bits 17 through 22 of word three refers to the transmitting satellite. The MSB indicates a summary of the health of the navigation data, where

0 = all navigation data is OK
1 = some or all navigation data is bad.

The five LSBs indicate the health of the signal components in accordance with the codes given in paragraph 2.4.5.3. The health indication is given relative to the "as designed" capabilities of each satellite (as designated by the configuration code -- see paragraph 2.4.5.4). Accordingly, any satellite which does not have a certain capability will be indicated as "healthy" if the lack of this capability is inherent in its design or it has been configured into a mode which is normal from a user standpoint and does not require that capability.

Additional satellite health data is given in subframes 4 and 5. The data given in subframe 1 may differ from that shown in subframes 4 and/or 5 of other satellite's since the latter may be updated at a different time.

2.4.3.4 Issue of Data, Clock

Bits 23 and 24 of word three in subframe 1 are the two MSBs of the ten-bit Issue of Data, Clock (IODC) term; bits one through eight of word eight in subframe 1 will contain the eight LSBs of the IODC. The IODC indicates the issue number of the data set and thereby provides the user with a convenient means of detecting any change in the correction parameters. The transmitted IODC will be different from any value transmitted by the satellite during the preceding seven days. The relationship between the IODC and the IODE (Issue Of Data, Ephemeris) terms are defined in Section 2.4.4.2.

2.4.3.5 Estimated Group Delay Differential

Bits 17 through 24 of word seven contain the correction term, T_{GD}, to account for the effect of satellite group delay differential. Application of the T_{GD} correction term is identified in Section 2.5.5.1.

2.4.3.6 Satellite Clock Correction Parameters

Bits nine through 24 of word eight, bits one through 24 of word nine, and bits one through 22 of word ten contain the parameters needed by the users for apparent satellite clock correction (t_{oc}, a_{f2}, a_{f1}, a_{f0}). Application of the clock correction parameters is identified in Section 2.5.5.2.

2.4.3.7 Reserved Data Fields

Table 2-3 provides the locations of reserved data fields within subframe 1. All reserved data fields support valid parity within their respective words.

Table 2-3. Subframe 1 Reserved Data Fields

Word	Bits
3	11-12
4	1-24
5	1-24
6	1-24
7	1-16

2.4.4 Subframes 2 and 3 - Satellite Ephemeris Data

Subframes 2 and 3 contain the ephemeris representation parameters of the transmitting satellite.

2.4.4.1 Ephemeris Parameters

Table 2-4 gives the definition of the orbital parameters using terminology typical of Keplerian orbital parameters; it is noted, however, that the transmitted parameter values are expressed in a coordinate system which allows the best trajectory fit in Earth fixed coordinates for each specific fit interval. The user will not interpret intermediate coordinate values as pertaining to any conventional or stable coordinate system.

For each parameter contained in subframe 2 and 3, the number of bits, the scale factor of the LSB (which is the last bit received), the range, and the units are as specified in Table 2-5.

Table 2-4. Ephemeris Data Definitions

M_0	Mean Anomaly at Reference Time
Δn	Mean Motion Difference from Computed Value
e	Eccentricity
$(A)^{1/2}$	Square Root of the Semi-Major Axis
$(OMEGA)_0$	Longitude of Ascending Node of Orbit Plane at Weekly Epoch
i_0	Inclination Angle at Reference Time
ω	Argument of Perigee
OMEGADOT	Rate of Right Ascension
IDOT	Rate of Inclination Angle
C_{uc}	Amplitude of the Cosine Harmonic Correction Term to the Argument of Latitude
C_{us}	Amplitude of the Sine Harmonic Correction Term to the Argument of Latitude
C_{rc}	Amplitude of the Cosine Harmonic Correction Term to the Orbit Radius
C_{rs}	Amplitude of the Sine Harmonic Correction Term to the Orbit Radius
C_{ic}	Amplitude of the Cosine Harmonic Correction Term to the Angle of Inclination
C_{is}	Amplitude of the Sine Harmonic Correction Term to the Angle of Inclination
t_{oe}	Reference Time Ephemeris
IODE	Issue of Data (Ephemeris)

Table 2-5. Ephemeris Parameters

Parameter	No. of Bits	Scale Factor (LSB)	Effective Range***	Units
IODE	8			(see text)
C_{rs}	16*	2^{-5}		meters
Δn	16*	2^{-43}		semi-circles/sec
M_0	32*	2^{-31}		semi-circles
C_{uc}	16*	2^{-29}		radians
e	32	2^{-33}	0.03	dimensionless
C_{us}	16*	2^{-29}		radians
$(A)^{1/2}$	32	2^{-19}		$meters^{1/2}$
t_{oe}	16	2^{4}	604,784	seconds
C_{ic}	16*	2^{-29}		radians
$(OMEGA)_0$	32*	2^{-31}		semi-circles
C_{is}	16*	2^{-29}		radians
i_0	32*	2^{-31}		semi-circles
C_{rc}	16*	2^{-5}		meters
ω	16*	2^{-31}		semi-circles
OMEGADOT	24*	2^{-43}		semi-circles/sec
IDOT	14*	2^{-43}		semi-circles/sec

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the MSB;
** See Figure 2-8 for complete bit allocation in subframe;
*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

2.4.4.2 Issue of Data, Ephemeris

The Issue of Data, Ephemeris (IODE) is an 8 bit number equal to the 8 LSBs of the 10 bit IODC of the same data set. The issue of ephemeris data (IODE) term will provide the user with a convenient means for detecting any change in the ephemeris representation parameters. The IODE is provided in both subframes 2 and 3 for the purpose of comparison with the 8 LSBs of the IODC term in subframe 1. Whenever these three terms do not match, a data set cutover has occurred and new data must be collected. The transmitted IODE will be different from any value transmitted by the satellite during the preceding six hours.

Any change in the subframe 2 and 3 data will be accomplished in concert with a change in both IODE words. Cutovers to new data sets will occur only on hour boundaries except for the first data set of a new upload. The first data set may be cut-in (reference paragraph 2.4.1.1) at any time during the hour and therefore may be transmitted by the satellite for less than one hour. Additionally, the t_{oe} value, for at least the first data set transmitted by an satellite after an upload, will be different from that transmitted prior to the cutover.

2.4.4.3 Spare and Reserved Data Fields

Table 2-6 provides the locations of spare and reserved data fields within Subframes 2 and 3. All spare and reserved data fields support valid parity within their respective words. Contents of spare data fields are alternating ones and zeros.

Table 2-6. Subframe 2 and 3 Spare and Reserved Data Fields

Word	Bits	Status
10	17	Reserved
10	18-22	Spare

2.4.5 Subframes 4 and 5 - Support Data

Both subframes 4 and 5 are subcommutated 25 times each; the 25 versions of these subframes are referred to as pages 1 through 25 of each subframe. With the possible exception of "spare" pages and explicit repeats, each page contains different data in words three through ten. As shown in Figure 2-8, the pages of subframe 4 use six different formats, while those of subframe 5 use two.

A brief summary of the various data contained in each page of subframes 4 and 5 is as follows:

a. Subframe 4:

- Pages 2, 3, 4, 5, 7, 8, 9, and 10: almanac data for satellite 25 through 32 respectively; These pages may be designated for other functions; the format and content for each page is defined by the satellite ID of that page. In this case, the six-bit health word of page 25 is set to "6 ones" (Refer to 2.4.5.3) and the satellite ID of the page will not have a value in the range of 25 through 32;
- Pages 17: special messages;
- Pages 18: ionospheric and UTC data;
- Page 25: satellite configurations for 32 satellites
- Pages 1, 6, 11, 12, 16, 19, 20, 21, 22, 23, and 24: (reserved):
- Pages 13, 14, and 15: spares;

b. Subframe 5:

- Pages 1 through 24: almanac data for satellite 1 through 24;
- Page 25: satellite health data for satellite 1 through 24, the almanac reference time and the almanac reference week number.

2.4.5.1 Data and Satellite IDs

The two MSBs of word three in each page contain the data ID which defines the applicable GPS navigation data structure. Data ID one (denoted by binary code) was utilized during Phase I of the GPS program and is no longer in use: data ID two (denoted by binary code 01) is described in this Signal Specification. Future data IDs will be defined as necessary.

As shown in Table 2-7, the data ID is utilized to provide one of two indications: (a) for those pages which are assigned to contain the almanac data of one specific satellite, the data ID defines the data structure utilized by that satellite whose almanac data are contained in that page; and (b) for all other pages, the data ID denotes the data structure of the transmitting satellite.

The satellite ID is given by bits three through eight of word three in each page, as shown in Table 3-6. Specific IDs are reserved for each page of subframe 4 and 5; however, the satellite ID of pages 2, 3, 4, 5, 7, 8, 9 and 10 of subframe 4 may change for each page to reflect the alternate contents for that page. The satellite IDs are utilized in two different ways: (a) for those pages which contain the almanac data of a given satellite, the satellite ID is the same number that is assigned to the PRN code phase of that satellite (reference Table 2-1), and (b) for all other pages the satellite ID assigned in accordance with Table 3-6 serves as the "page ID". IDs 1 through 32 are assigned to those pages which contain the almanac data of specific satellites (pages 1-24 of subframe 5 and pages 2-5 plus 7-10 of subframe 4). The "0" ID (binary all zeros) is assigned to indicate a dummy satellite, while IDs 51 through 63 are utilized for pages containing other than almanac data of a specific satellite. The remaining IDs (33 through 50) are unassigned.

Pages which contain identical data (for more frequent repetition) carry the same satellite ID (e.g., in subframe 4, pages 1, 6, 11, and 21 carry an ID of 57, while pages 12 and 24 are designated by an ID of 62).

2.4.5.2 Almanac

Pages 1 through 24 of subframe 5, as well as pages 2 through 5 and 7 through 10 of subframe 4 contain the almanac data and a satellite health word for up to 32 satellites (the health word is discussed in paragraph 2.4.5.3). The almanac data are a reduced-precision subset of the clock and ephemeris parameters. The data occupy all bits of words three through ten of each page except the eight MSBs of word three (data ID and satellite ID), bits 17 through 24 of word five (satellite health), and the 50 bits devoted to parity. The number of bits, the scale factor (LSB), the range, and the units of the almanac parameters are given in Table 2-8. The almanac message for any dummy satellite will contain alternating ones and zeros with valid parity.

2.4.5.2.1 Almanac Reference Time

The almanac reference time, t_{oa}, is nominally the multiple of 2^{12} seconds truncated from 3.5 days after the first valid transmission time for this almanac data set. The almanac is updated often enough to ensure that GPS time, t, will differ from t_{oa} by less than 3.5 days during the transmission period. The almanac parameters are updated at least once every 6 days during normal operations.

2.4.5.2.2 Almanac Time Parameters

The almanac time parameters consist of an 11-bit constant term (a_{f0}) and an 11-bit first order term (a_{f1}).

Table 2-7. Data IDs and Satellite IDs in Subframes 4 and 5

Page	Subframe 4		Subframe 5	
	Data ID	satellite ID*	Data ID	satellite ID*
1	Note (2)	57	Note (1)	1
2 Note (3)	Note (1)	25	Note (1)	2
3 Note (3)	Note (1)	26	Note (1)	3
4 Note (3)	Note (1)	27	Note (1)	4
5 Note (3)	Note (1)	28	Note (1)	5
6	Note (2)	57	Note (1)	6
7 Note (3)	Note (1)	29	Note (1)	7
8 Note (3)	Note (1)	30	Note (1)	8
9 Note (3)	Note (1)	31	Note (1)	9
10 Note (3)	Note (1)	32	Note (1)	10
11	Note (2)	57	Note (1)	11
12	Note (2)	62	Note (1)	12
13	Note (2)	52	Note (1)	13
14	Note (2)	53	Note (1)	14
15	Note (2)	54	Note (1)	15
16	Note (2)	57	Note (1)	16
17	Note (2)	55	Note (1)	17
18	Note (2)	56	Note (1)	18
19	Note (2)	58 Note (4)	Note (1)	19
20	Note (2)	59 Note (4)	Note (1)	20
21	Note (2)	57	Note (1)	21
22	Note (2)	60 Note (4)	Note (1)	22
23	Note (2)	61 Note (4)	Note (1)	23
24	Note (2)	62	Note (1)	24
25	Note (2)	63	Note (2)	51

* Use "0" to indicate "dummy" satellite. When using "0" to indicate dummy satellite, use the data ID of the transmitting satellite.

Note 1: Data ID of that satellite whose satellite ID appears in that page.

Note 2: Data ID of transmitting satellite.

Note 3: Pages 2, 3, 4, 5, 7, 8, 9, and 10 of subframe 4 may contain almanac data for satellites 25 through 32, respectively, or data for other functions as identified by a different satellite ID from the value shown.

Note 4: Satellite ID may vary.

Table 2-8. Almanac Parameters

Parameter	No. of Bits	Scale Factor (LSB)	Effective Range***	Units
e	16	2^{-21}		dimensionless
t_{oa}	8	2^{12}	602,112	seconds
δ_i****	16*	2^{-19}		semi-circles
OMEGADOT	16*	2^{-38}		semi-circles/sec
$(A)^{1/2}$	16*	2^{-11}		$\text{meters}^{1/2}$
$(\text{OMEGA})_0$	24*	2^{-23}		semi-circles
ω	24*	2^{-23}		semi-circles
M_0	24*	2^{-23}		semi-circles
a_{f0}	11*	2^{-20}		seconds
a_{f1}	11*	2^{-38}		sec/sec

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the MSB;

** See Figure 2-8 for complete bit allocation in subframe;

*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor

**** Relative to i_0 = 0.30 semi-circles.

2.4.5.2.3 Almanac Reference Week

Bits 17 through 24 of word three in page 25 of subframe 5 will indicate the number of the week (WN_a) to which the almanac reference time (t_{oa}) is referenced. The WN_a term consists of the eight LSBs of the full week number. Bits 9 through 16 of word three in page 25 of subframe 5 will contain the value of t_{oa} which is referenced to this WN_a.

2.4.5.3 Health Summary

Subframes 4 and 5 contain two types of satellite health data: (a) each of the 32 pages which contain the clock/ephemeris related almanac data provide an eight-bit satellite health status word regarding the satellite whose almanac data they carry, and (b) the 25th pages of subframe 4 and of subframe 5 jointly contain six-bit health status data for up to 32 satellites.

The eight-bit health status words occupy bits 17 through 24 of word five in those 32 pages which contain almanac data for individual satellites. The six-bit health status words occupy the 24 MSBs of words four through nine in page 25 of subframe 5 plus bits 19 through 24 of word 8, the 24 MSBs of word 9, and the 18 MSBs of word 10 in page 25 of subframe 4.

The three MSBs of the eight-bit health words indicate health of the navigation data in accordance with the code given in Table 2-9. The six-bit words provide a one-bit summary of the navigation data's health status in the MSB position in accordance with paragraph 2.4.3.3. The five LSBs of both the eight-bit and the six-bit health words provide the health status of the satellites signal components in accordance with the code given in Table 2-10. A special meaning is assigned, however, to the "6 ones" combination of the six-bit health words in the 25th pages of subframes 4 and 5: it indicates that "the satellite which has that ID is not available and there may be no data regarding that satellite in that page of subframes 4 or 5 that is assigned to normally contain the almanac data of that satellite" (NOTE: (a) this special meaning applies to the 25th pages of subframes 4 and 5 only; and (b) there may be data regarding another satellite in the almanac-page referred to above as defined in paragraph 2.4.5.1). The health indication shall be given relative to the "as designed" capabilities of each satellite (as designated by the configuration code - see paragraph 2.4.5.4). Accordingly, any satellite which does not have a certain capability will be indicated as "healthy" if the lack of this capability is inherent in its design or it has been configured into a mode which is normal from a user standpoint and does not require that capability.

Table 2-9. Navigation Data Health Indications

BIT POSITION IN PAGE			INDICATION
137	138	139	
0	0	0	ALL DATA OK
0	0	1	PARITY FAILURE -- some or all parity bad
0	1	0	TLM/HOW FORMAT PROBLEM -- any departure from standard format (e.g., preamble misplaced and/or incorrect, etc.), except for incorrect Z-count, as reported in HOW
0	1	1	Z-COUNT IN HOW BAD -- any problem with Z-count value not reflecting actual code phase
1	0	0	SUBFRAMES 1, 2, 3 -- one or more elements in words three through ten of one or more subframes are bad.
1	0	1	SUBFRAMES 4, 5 -- one or more elements in words three through ten of one or more subframes are bad.
1	1	0	ALL UPLOADED DATA BAD -- one or more elements in words three through ten of any one (or more) subframes are bad.
1	1	1	ALL DATA BAD -- TLM word and/or HOW and one or more elements in any one (or more) subframes are bad.

Table 2-10. Codes for Health of Satellite Signal Components

MSB				LSB	
0	0	0	0	0	⇒ ALL SIGNALS OK
1	1	1	0	0	⇒ SATELLITE <u>IS</u> TEMPORARILY OUT~do not use this satellite during current pass**
1	1	1	0	1	⇒ SATELLITE <u>WILL BE</u> TEMPORARILY OUT~ use with caution**
1	1	1	1	0	⇒ SPARE
1	1	1	1	1	⇒ MORE THAN ONE COMBINATION WOULD BE REQUIRED TO DESCRIBE ANOMALIES, EXCEPT THOSE MARKED BY **
All Other Combinations					⇒ SATELLITE EXPERIENCING CODE MODULATION AND/OR SIGNAL POWER LEVEL TRANSMISSION PROBLEMS. Modulated navigation data valid, however user may experience intermittent tracking problems if satellite is acquired.

The predicted health data will be updated at the time of upload. The transmitted health data may not correspond to the actual health of the transmitting satellite or other satellites in the constellation. The data given in subframes 1, 4, and 5 of the other satellites may differ form that shown in subframes 4 and/or 5 since the latter may be updated at a different time.

2.4.5.4 Satellite Configuration Summary

Page 25 of subframe 4 contains a four-bit-long term for each of up to 32 satellites to indicate the configuration code of each satellite. The first MSB of each field is reserved. The three LSBs indicate the configuration of each satellite using the following code:

<u>Code</u>	<u>Satellite Configuration</u>
000	"Block I" satellite.
001	"Block II" satellite.

These four-bit terms occupy bits 9 through 24 of word three, the 24 MSBs of words four through seven, and the 16 MSBs of word eight, all in page 25 of subframe 4.

2.4.5.5 Universal Coordinated Time (UTC) Parameters

Page 18 of subframe 4 includes: (1) the parameters needed to relate GPS time to UTC, and (2) notice to the user regarding the scheduled future or recent past (relative to navigation message upload) value of the delta time due to leap seconds (Δt_{LSF}), together with the week number (WN_{LSF}) and the day number (DN) at the end of which the leap second becomes effective. "Day one" is the first day relative to the end/start of week and the WN_{LSF} value consists of the eight LSBs of the full week number. The user must account for the truncated nature of this parameter as well as truncation of WN, WN_t, and W_{LSF} due to rollover of the full week number (see paragraph 2.3.5(b)). The absolute value of the difference between the untruncated WN and WN_{LSF} values will not exceed 127.

The 24 MSBs of words six through nine plus the eight MSBs of word ten in page 18 of subframe 4 contain the parameters related to correlating UTC time with GPS time. The bit length, scale factors, ranges, and units of these parameters are given in Table 2-11. The related algorithms are described in paragraph 2.5.6.

Table 2-11. UTC Parameters

Parameter	No. of Bits	Scale Factor (LSB)	Effective Range***	Units
A_0	32*	2^{-30}		seconds
A_1	24*	2^{-50}		sec/sec
Δt_{LS}	8	1		seconds
t_{ot}	8	2^{12}	602,112	seconds
WN_t	8	1		weeks
WN_{LSF}	8	1		weeks
DN	8****	1	7	days
Δt_{LSF}	8*	1		seconds

* Parameters so indicated is two's complement, with the sign bit (+ or -) occupying the MSB;
** See Figure 2-8 for complete bit allocation in subframe;
*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.
**** Right justified.

2.4.5.6 Ionospheric Parameters

The ionospheric parameters which allow the SPS user to utilize the ionospheric model (reference paragraph 2.5.5.3) for computation of the ionospheric delay are contained in page 18 of subframe 4. They occupy bits 9 through 24 of word three plus the 24 MSBs of words four and five. The bit lengths, scale factors, ranges, and units of these parameters are given in Table 2-12.

Table 2-12. Ionospheric Parameters

Parameter	No. of Bits	Scale Factor (LSB)	Effective Range***	Units
α_0	8 *	2^{-30}		seconds
α_1	8 *	2^{27}		sec. per semi-circle
α_2	8 *	2^{-24}		sec. per semi-circles^2
α_3	8 *	2^{-24}		sec. per semi-circles^3
β_0	8 *	2^{11}		seconds
β_1	8 *	2^{14}		sec. per semi-circles
β_2	8 *	2^{16}		sec. per semi-circles^2
β_3	8 *	2^{16}		sec. per semi-circles^3

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the MSB;
** See Figure 2-8 for complete bit allocation in subframe;
*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

2.4.5.7 Special Message

Page 17 of subframe 4 is reserved for special messages with the specific contents at the discretion of the system operator. It will accommodate the transmission of 22 eight-bit ASCII characters. The requisite 176 bits will occupy bits 9 through 24 of word three, the 24 MSBs of words four through nine, plus the 16 MSBs of word ten. The eight MSBs of word three contain the data ID and satellite ID, while bits 17 through 22 of word ten are spares containing alternating ones and zeros. The remaining 50 bits of words three through ten are used for parity (six bits/word) and parity computation (two bits in word ten). The eight-bit ASCII characters is limited to the following set:

Alphanumeric Character	ASCII Character	Code (Octal)
A - Z	A - Z	101 - 132
0 - 9	0 - 9	060 - 071
+	+	053
-	-	055
. (Decimal point)	.	056
' (Minute mark)	'	047
° (Degree sign)	°	370
/	/	057
Blank	Space	040
:	:	072
" (Second mark)	"	042

2.4.5.8 Spare Data Fields

All bits of words three through ten, except the 58 bits used for data ID, satellite (page) ID, parity (six LSBs of each word) and parity computation (bits 23 and 24 of word ten) of pages 13, 14 and 15 of subframe 4, and those almanac pages assigned satellite ID of zero are designated as spares. In addition, as shown in Table 2-13, several smaller groups of spare bits exist in subframes 4 and 5. These spare bit positions of each word will contain a pattern of alternating ones and zeroes with valid word parity.

Table 2-13. Spare Bits in Subframes 4 and 5

Subframe	**Pages**	**Words**	**Spare Bit Position in Word**
4	12, 19, 20, 22, 23, 24	9	9 - 24
4	1, 6, 11, 12, 16, 19, 20, 21, 22, 23, 24	10	1 - 22
4	17	10	17 - 22
4	18	10	9 - 22
4	25	8	17 - 18
4	25	10	19 - 22
5	25	10	4 - 22

NOTE: In addition, all bits of words three through ten in pages 13, 14, and 15 of subframe 4 (except the 58 bits used for data ID, satellite (page) ID, parity and parity computation) are also designated as spares.

2.5 User Algorithms

This section provides guidance in the implementation of measurement processing algorithms. The discussions in this section include:

- Mathematical constants used in GPS position determination computations.
- The GPS parity algorithm implementation to permit the user to detect demodulation errors within the decoded navigation message.
- Interpretation of the satellite transmitted URA parameter.
- Satellite position determination using broadcast ephemeris parameters.
- Correction of the code phase time received from the satellite with respect to both satellite code phase offset and relativistic effects.
- Compensation for the effects of satellite group delay differential.
- Correction for ionospheric propagation delay.
- Performing time transfer to UTC.
- Use of almanac data and time parameters.

2.5.1 Mathematical Constants

The speed of light used for generating the data described in the above paragraphs is:

$$c = 2.99792458 \times 10^{8} \text{ meters per second}$$

which is the official WGS-84 speed of light. The user should use the same value for the speed of light in computations. Other WGS-84 constants the user is required to use for satellite ephemeris calculations are:

$\mu = 3.986005 \times 10^{14}$ meters^3 / sec^2	WGS-84 value of the Earth's universal gravitational parameter
$\Omega_e = 7.2921151467 \times 10^{-5}$ rad / sec	WGS-84 value of the Earth's rotation rate

The sensitivity of the satellite's antenna phase center position to small perturbations in most ephemeris parameters is extreme. The sensitivity of position to the parameters $(A)^{1/2}$, C_{rc} and C_{rs} is about one meter/meter. The sensitivity of position to the angular rate parameters is on the order of 10^8 meters/semicircle, and to the angular rate parameters is on the order of 10^{12} meter/semicircle/second. Because of this extreme sensitivity to angular perturbations, the value of π used in the curve fit is given here. π is a mathematical constant, the ratio of a circle's circumference to its diameter. Here π is taken as

$$\pi = 3.1415926535898$$

2.5.2 Parity Algorithm

The user must perform error detection of the decoded navigation data using the parity algorithm equations provided in Table 2-14. Figure 2-10 presents an example flow chart that defines one way of recovering data (d_n) and checking parity. The parity bit D^*_{30} is used for recovering raw data. The parity bits D^*_{29} and D^*_{30}, along with the recovered raw data (d_n) are modulo-2 added in accordance with the equations appearing in Table 2-14 for $D_{25} \ldots D_{30}$, which provide computed parity to compare with transmitted parity $D_{25} \ldots D_{30}$.

Table 2-14. Parity Encoding Equations

$D_1 = d_1 \oplus D_{30}^*$

$D_2 = d_2 \oplus D_{30}^*$

$D_3 = d_3 \oplus D_{30}^*$

• •
• •
• •
• •

$D_{24} = d_{24} \oplus D_{30}^*$

$D_{25} = D_{29}^* \oplus d_1 \oplus d_2 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_{10} \oplus d_{11} \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{17} \oplus d_{18} \oplus d_{20} \oplus d_{23}$

$D_{26} = D_{30}^* \oplus d_2 \oplus d_3 \oplus d_4 \oplus d_6 \oplus d_7 \oplus d_{11} \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{18} \oplus d_{19} \oplus d_{21} \oplus d_{24}$

$D_{27} = D_{29}^* \oplus d_1 \oplus d_3 \oplus d_4 \oplus d_5 \oplus d_7 \oplus d_8 \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{19} \oplus d_{20} \oplus d_{22}$

$D_{28} = D_{30}^* \oplus d_2 \oplus d_4 \oplus d_5 \oplus d_6 \oplus d_8 \oplus d_9 \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{17} \oplus d_{20} \oplus d_{21} \oplus d_{23}$

$D_{29} = D_{30}^* \oplus d_1 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_7 \oplus d_9 \oplus d_{10} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{17} \oplus d_{18} \oplus d_{21} \oplus d_{22} \oplus d_{24}$

$D_{30} = D_{29}^* \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_8 \oplus d_9 \oplus d_{10} \oplus d_{11} \oplus d_{13} \oplus d_{15} \oplus d_{19} \oplus d_{22} \oplus d_{23} \oplus d_{24}$

where:

$d_1, d_2, \ldots d_{24}$ are the source data bits

the symbol (*) is used to identify the last 2 bits of the previous word of the subframe,

$D_{25}, \ldots D_{30}$ are the computed parity bits

$D_1, D_2, D_3, \ldots D_{29}, D_{30}$ are the bits transmitted by the satellite, and

$\oplus$ is the "Modulo-2" or "Exclusive-Or" operation.

2.5.3 User Range Accuracy

The URA reported in the navigation message will correspond to the maximum value anticipated during each subframe fit interval with uniform SA levels invoked. Referring to the decimal equivalent of the transmitted four-bit binary number as N -- with N a positive integer in the range of 0 through 15 -- the accuracy value is defined to mean "no better than X meters", in accordance with the following relationships:

- If the value of N is 6 or less, $X = 2^{(1 + N/2)}$,
- If the value of N is 6 or more, but less than 15, $X = 2^{(N-2)}$,
- N = 15 will indicate the absence of an accuracy prediction and will advise the SPS user to use that satellite at the user's own risk.

For N = 1, 3, and 5, X is rounded to 2.8, 5.7, and 11.3 meters respectively; the above relationships yield integer values of X for all other values of N. Using these values of X the user may utilize a look-up table approach for interpreting the URA message.

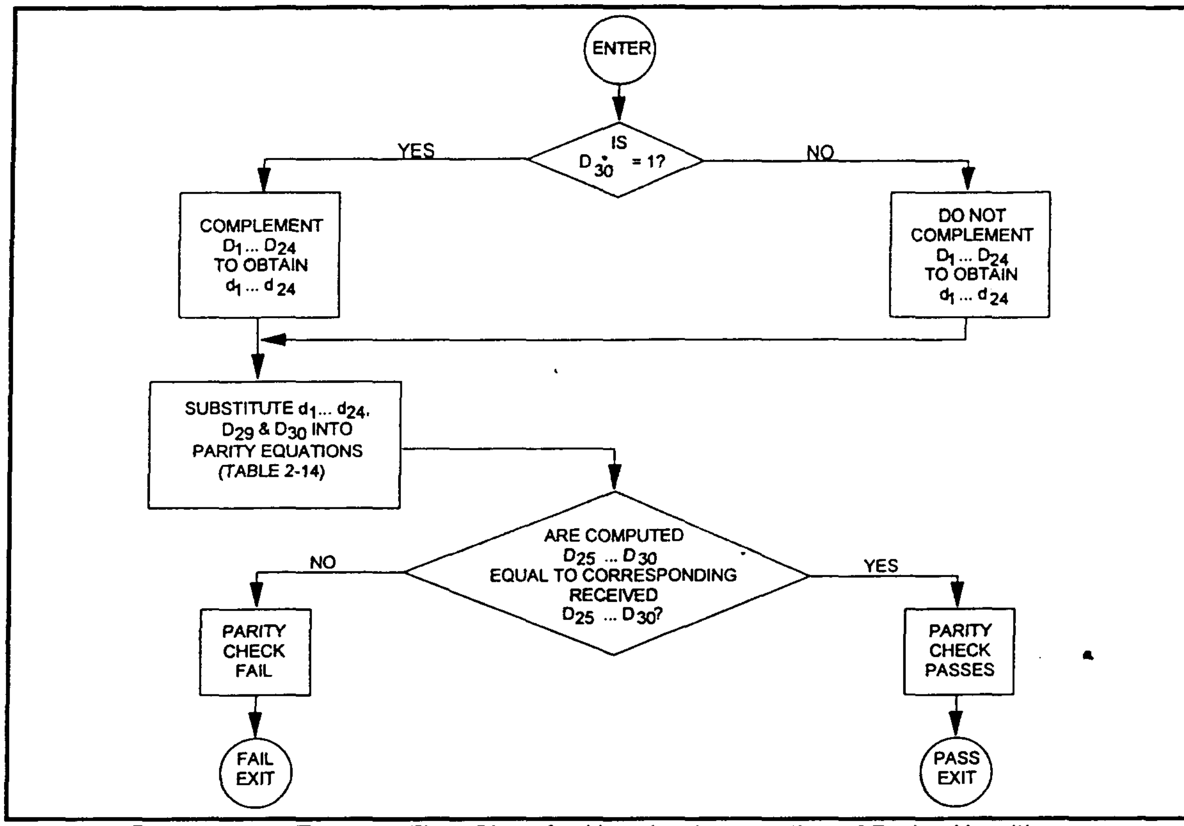


Figure 2-10. Example Flow Chart for User Implementation of Parity Algorithm

2.5.4 User Algorithm for Ephemeris Determination

The user will compute the ECEF coordinates of position for the phase center of each satellite's L-Band antenna utilizing a variation of the equations shown in Table 2-15. Subframes 2 and 3 parameters are Keplerian in appearance; the values of these parameters, however, are obtained via a least squares curve fit of the predicted ephemeris for the phase center of the satellite's antenna (time-position quadruples; t, x, y, z).

2.5.4.1 Coordinate System

The equations given in Table 2-15 provide the satellite's antenna phase center position in the WGS-84 Earth-Centered Earth-Fixed reference frame defined as follows:

ORIGIN = Earth's center of mass*

Z-AXIS = Parallel to the direction of the CONVENTIONAL INTERNATIONAL ORIGIN (CIO) for polar motion, as defined by the BUREAU INTERNATIONAL DE L'HEURE (BIH) on the basis of the latitudes adopted for the BIH stations**

X-AXIS = Intersection of the WGS-84 reference meridian plane and the plane of the mean astronomic equator, the reference meridian being parallel to the zero meridian defined by the BUREAU INTERNATIONAL DE L'HEURE (BIH) on the basis of the longitudes adopted for the BIH stations***

Y-AXIS = Completes a right-handed Earth-Centered, Earth-Fixed orthogonal coordinate system, measured in the plan of the mean astronomic equator 90 degrees east of the X-axis***

* Geometric center of WGS-84 ellipsoid

** Rotation axis of WGS-84 ellipsoid

*** X, Y axis of WGS-84 ellipsoid

Table 2-15. Elements of Coordinate Systems

$A = \left(\sqrt{A}\right)^2$	Semi-major axis
$n_0 = \sqrt{\dfrac{\mu}{A^3}}$	Computed mean motion - rad/sec
$t_k = t - t_{oe}$ *	Time from ephemeris reference epoch
$n = n_0 + \Delta n$	Corrected mean motion
$M_k = M_0 + n t_k$	Mean anomaly
$M_k = E_k - e \sin E_k$	Kepler's equation for eccentric anomaly (may be solved by iteration) - radians
$\nu_k = \tan^{-1}\left\{\dfrac{\sin\nu_k}{\cos\nu_k}\right\} = \tan^{-1}\left\{\dfrac{\sqrt{1-e^2}\sin E_k \;/\; (1 - e\cos E_k)}{(\cos E_k - e) \;/\; (1 - e\cos E_k)}\right\}$	True anomaly
$E_k = \cos^{-1}\left\{\dfrac{e + \cos\nu_k}{1 + e\cos\nu_k}\right\}$	Eccentric anomaly
$\Phi_k = \nu_k + \omega$	Argument of latitude
	<u>Second Harmonic Perturbations</u>
$\delta u_k = C_{us} \sin 2\Phi_k + C_{uc} \cos 2\Phi_k$	Argument of latitude correction
$\delta r_k = C_{rc} \cos 2\Phi_k + C_{rs} \sin 2\Phi_k$	Radius correction
$\delta i_k = C_{ic} \cos 2\Phi_k + C_{is} \sin 2\Phi_k$	Correction to inclination
$u_k = \Phi_k + \delta u_k$	Corrected argument of latitude
$r_k = A(1 - e\cos E_k) + \delta r_k$	Corrected radius
$i_k = i_0 + \delta i_k + (\mathrm{IDOT})\, t_k$	Corrected inclination
$\left.\begin{array}{l} x_k' = r_k \cos u_k \\ y_k' = r_k \sin u_k \end{array}\right\}$	Positions in orbital plane
$\Omega_k = \Omega_0 + (\dot{\Omega} - \dot{\Omega}_e)\, t_k - \dot{\Omega}_e\, t_{oe}$	Corrected longitude of ascending node
$\left.\begin{array}{l} x_k = x_k' \cos\Omega_k - y_k' \cos i_k \sin\Omega_k \\ y_k = x_k' \sin\Omega_k + y_k' \cos i_k \cos\Omega_k \\ z_k = y_k' \sin i_k \end{array}\right\}$	Earth-Centered, Earth-Fixed coordinates

* t is GPS system time at time of transmission, i.e., GPS time corrected for transit time (range/speed of light). Furthermore, t_k shall be the actual total time difference between the time t and the epoch time t_{oe}, and must account for beginning or end of week crossovers. That is, if t_k is greater than 302,400 seconds, subtract 604,800 seconds from t_k. If t_k is less than -302,400 seconds, add 604,800 seconds to t_k.

2.5.4.2 Geometric Range Correction

When computing the geometric range, the user will account for the effects due to earth rotation rate (reference Table 2-15) during the time of signal propagation so as to evaluate the path delay in an inertially stable coordinate system. Specifically, if the user works in Earth-fixed coordinates the user should add $(-\dot{\Omega}_e y\Delta t, \dot{\Omega}_e x\Delta t, 0)$ to the position estimate (x, y, z).

2.5.5 Application of Correction Parameters

In order to properly account for satellite clock bias and propagation delays, the user receiver must perform corrections to observed pseudo range measurements. The pseudo range is defined as:

$$PR_{measured} = c(t_{received} - t_{transmitted})$$

where

$PR_{measured}$ = measured pseudo range
$t_{received}$ = time that ranging measurement was received at the user location
$t_{transmitted}$ = time that ranging signal was transmitted from the satellite

The system application of the correction parameters for user receiver pseudorange measurements is shown in Figure 2-11. The ionospheric model referred to in Figure 2-11 is discussed in paragraph 2.5.5.3 using the related data contained in page 18 of subframe 4.

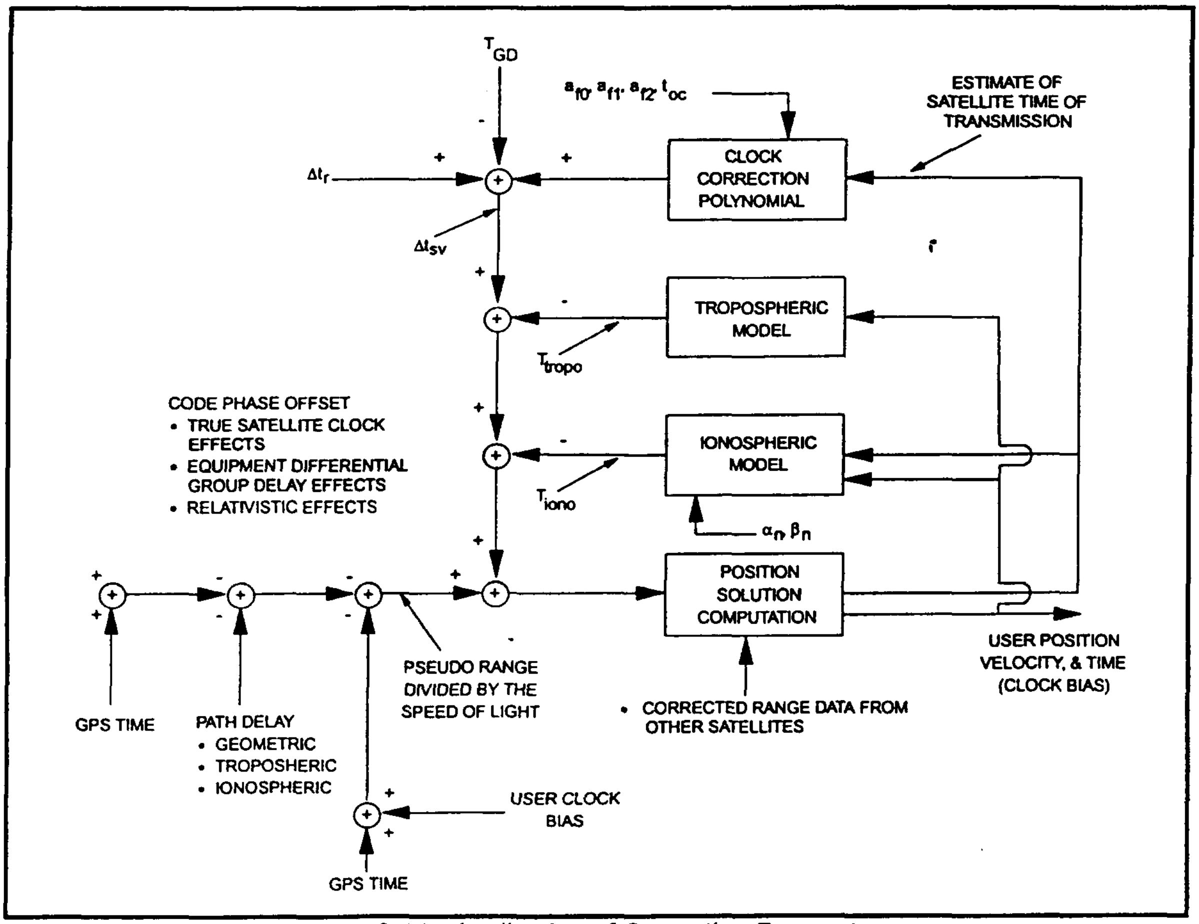


Figure 2-11. Application of Correction Parameters

2.5.5.1 Group Delay Application

The SPS user who utilizes the L1 frequency will modify the code phase offset with the equation:

$$(\Delta t_{SV})_{L1} = \Delta t_{SV} - T_{GD}$$

where T_{GD} is provided to the user as subframe 1 data.

2.5.5.2 Satellite Clock Correction

The polynomial defined in the following allows the user to determine the effective satellite PRN code phase offset referenced to the phase center of the satellite antennas (Δt_{SV}) with respect to GPS system time (t) at the time of data transmission.

The coefficients transmitted in subframe 1 describe the offset apparent to the control segment two-frequency receivers for the interval of time in which the parameters are transmitted. This estimated correction accounts for the deterministic satellite clock error characteristics of bias, drift and aging, as well as for the satellite implementation characteristics of group delay bias and mean differential group delay. Since these coefficients do not include corrections for relativistic effects, the user's equipment must determine the requisite relativistic correction. Accordingly, the offset given below includes a term to perform this function.

The user will correct the time received from the satellite with the equation (in seconds)

$$t = t_{sv} - (\Delta t_{sv})_{L1} \qquad (1)$$

where

$$\begin{aligned} t &= \text{GPS system time (seconds)}, \\ t_{sv} &= \text{effective SV PRN code phase time at message transmission time (seconds)}, \\ (\Delta t_{sv})_{L1} &= \text{SV PRN code phase time offset (seconds)}. \end{aligned}$$

The satellite PRN code phase offset is given by

$$(\Delta t_{sv})_{L1} = a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}(t - t_{oc})^2 + \Delta t_r - T_{GD} \qquad (2)$$

where a_{f0}, a_{f1}, and a_{f2} are the polynomial coefficients given in subframe 1, t_{oc} is the clock data reference time in seconds, and Δt_r is the relativistic correction term (seconds) which is given by

$$\Delta t_r = F e (A)^{1/2} \sin E_k .$$

The orbit parameters (e, A, E_k) used here are described in discussions of data contained in subframes 2 and 3, while F is a constant whose value is

$$F = \frac{-2(\mu)^{1/2}}{c^2} = -4.442807633 \, (10)^{-10} \text{ sec} / (\text{meter})^{1/2} .$$

Note that equations (1) and (2), as written, are coupled. While the coefficients a_{f0}, a_{f1}, and a_{f2} are generated by using GPS time as indicated in equation (2), sensitivity of t_{sv} to t is negligible. This negligible sensitivity will allow the user to approximate t by t_{sv} in equation (2). The value of t must account for beginning or end of week crossovers. That is, if the quantity t - t_{oc} is greater than 302,400 seconds, subtract 604,800 seconds from t. If the quantity t - t_{oc} is less than -302,400 seconds, add 604,800 seconds to t.

2.5.5.3 Ionospheric Model

The SPS user should correct the time received from the satellite for ionospheric effect by utilizing parameters contained in page 18 of subframe 4 in the model given below. It is estimated that the use of this model will provide at least a 50 percent reduction in the SPS user's RMS error due to ionospheric propagation effects.

The ionospheric correction model is given by

$$T_{iono} = \left\{ \begin{array}{ll} F * \left[5.0 * 10^{-9} + (AMP)\left(1 - \frac{x^2}{2} + \frac{x^4}{24}\right)\right], & |x| < 1.57 \\ F * (5.0 * 10^{-9}), & |x| \geq 1.57 \end{array} \right\} (sec)$$

where

$$AMP = \left\{ \begin{array}{l} \sum_{n=0}^{3} \alpha_n \ \phi_m^n, \ AMP \geq 0 \\ \text{if } AMP < 0, \ AMP = 0 \end{array} \right\} (sec)$$

$$x = \frac{2\pi(t - 50400)}{PER}, \ (radians)$$

$$PER = \left\{ \begin{array}{l} \sum_{n=0}^{3} \beta_n \ \phi_m^n, \ PER \geq 72{,}000 \\ \text{if } PER < 72{,}000, \ PER = 72{,}000 \end{array} \right\} (sec)$$

$F = 1.0 + 16.0[0.53 - E]^3$, and
α_n and β_n are the satellite transmitted data words with n = 0, 1, 2, and 3.

Other equations that must be solved are

$$\phi_m = \phi_i + 0.064 \cos(\lambda_i - 1.617) \ (\text{semi-circles}),$$

$$\lambda_i = \lambda_u + \frac{\psi \sin A}{\cos \phi_i} \ (\text{semi-circles}),$$

$$\phi_i = \left\{ \begin{array}{l} \phi_u + \psi \cos A (\text{semi-circles}), \ |\phi_i| \leq 0.416 \\ \text{if } \phi_i > 0.416, \text{ then } \phi_i = +0.416 \\ \text{if } \phi_i < -0.416, \text{ then } \phi_i = -0.416 \end{array} \right\} (\text{semi-circles}),$$

$$\psi = \frac{0.00137}{E + 0.11} - 0.022 \ (\text{semi-circles}),$$

$$t = 4.32 * 10^4 \ \lambda_i + \text{GPS time (sec)}$$

where

$0 \leq t < 86400$, therefore: if $t \geq 86400$ seconds, subtract 86400 seconds;
if $t < 0$ seconds, add 86400 seconds.

The terms used in computation of ionospheric delay are as follows:

- Satellite Transmitted Terms

α_n	the coefficients of a cubic equation representing the amplitude of the vertical delay (4 coefficients = 8 bits each)
β_n	the coefficients of a cubic equation representing the period of the model (4 coefficients = 8 bits each)

- Receiver Generated Terms

E	elevation angle between the user and satellite (semi-circles)
A	azimuth angle between the user and satellite, measured clockwise positive from the true North (semi-circles)
ϕ_u	user geodetic latitude (semi-circles) WGS-84
λ_u	user geodetic longitude (semi-circles) WGS-84
GPS time	receiver computed system time

- Computed Terms

x	phase (radians)
F	obliquity factor (dimensionless)
t	local time (sec)
ϕ_m	geomagnetic latitude of the earth projection of the ionospheric intersection point (mean ionospheric height assumed 350 km) (semicircles)
λ_i	geomagnetic latitude of the earth projection of the ionospheric intersection point (semi-circles)
ϕ_i	geomagnetic latitude of the earth projection of the ionospheric intersection point (semi-circles)
ψ	earth's central angle between user position and earth projection of ionospheric intersection point (semi-circles)

2.5.6 Universal Coordinated Time (UTC)

Depending upon the relationship of the effectivity date to the user's current GPS time, the following three different UTC/GPS-time relationships exist:

a. Whenever the effectivity time indicated by the WN_{LSF} and the DN values is not in the past (relative to the user's present time), <u>and</u> the user's present time does not fall in the timespan which starts at DN + 3/4 and ends at DN + 5/4, the UTC/GPS-time relationship is given by

$$t_{UTC} = (t_E - \Delta t_{UTC}) \ \{\text{Modulo 86400 seconds}\}$$

where t_{UTC} is in seconds and

$$\Delta t_{UTC} = \Delta t_{LS} + A_0 + A_1 (t_E - t_{ot} + 604800\,(WN - WN_t)), \ \text{(seconds)};$$

t_E = GPS time as estimated by the user on the basis of correcting t_{sv} for factors described in paragraph 2.5.5.2 as well as for ionospheric and SA (dither) effects;

Δt_{LS} = delta time due to leap seconds;

A_0 and A_1 = constant and first order terms of polynomial;

t_{ot} = reference time for UTC data;

WN = current week number (derived from subframe 1);

WN_t = UTC reference week number.

The estimated GPS time (t_E) is in seconds relative to end/start of week. The reference time for UTC data (t_{ot}) is referenced to the start of that week whose number (WN_t) is given in word eight of page 18 in subframe 4. The WN_t value consists of the eight LSBs of the full week number. The user must account for the truncated nature of this parameter as well as truncation of WN, WN_t, and W_{LSF} due to rollover of the full week number (see paragraph 2.3.5(b)). The absolute value of the difference between the untruncated WN and WN_t values will not exceed 127.

b. Whenever the user's current time falls within the timespan of DN + 3/4 to DN + 5/4, proper accommodation of the leap second event with a possible week number transition is provided by the following expression for UTC:

$$t_{UTC} = W\left[\text{Modulo}\left(86400 + \Delta t_{LSF} - \Delta t_{LS}\right)\right], \text{ (seconds)};$$

where

$$W = \left(t_E - \Delta t_{UTC} - 43200\right)\left[\text{Modulo } 86400\right] + 43200, \text{ (seconds)};$$

and the definition of Δt_{UTC} (as given in "a" above) applies throughout the transition period. Note that when a leap second is added, unconventional time values of the form 23: 59: 60.xxx are encountered. Some user equipment may be designed to approximate UTC by decrementing the running count of time within several seconds after the event, thereby promptly returning to a proper time indication. Whenever a leap second event is encountered, the user equipment must consistently implement carries or borrows into any year/week/day counts.

c. Whenever the effectivity time of the leap second event, as indicated by the WN_{LSF} and DN values, is in the "past" (relative to the user's current time), the relationship previously given for t_{UTC} in "a" above is valid except that the value of Δt_{LSF} is substituted for Δt_{LS}. The CS will coordinate the update of UTC parameters at a future upload so as to maintain a proper continuity of the t_{UTC} time scale.

2.5.7 Almanac Data

The almanac is a subset of the clock and ephemeris data, with reduced precision. The user algorithm is essentially the same as the user algorithm used for computing the precise ephemeris from the subframe 1, 2, and 3 parameters (see Table 2-15). The almanac content for one satellite is given in Table 2-8. A close inspection of Table 2-8 will reveal that a nominal inclination angle of 0.30 semicircles is implicit and that the parameter δi (correction to inclination) is transmitted, as opposed to the value being computed by the user. All other parameters appearing in the equations of Table 2-15, but not included in the content of the almanac, are set to zero for satellite position determination. In these respects, the application of the Table 2-15 equations differs between the almanac and the ephemeris computations.

Almanac time is computed using a first-order polynomial. The applicable first order polynomial, which will provide time to within 2 microseconds of GPS time (t) during the interval of applicability, is given by

$$t = t_{sv} - \Delta t_{sv}$$

where

t = GPS system time (seconds)

t_{SV} = effective satellite PRN code phase time at message transmission time (seconds),

Δt_{sv} = satellite PRN code phase time offset (seconds).

The satellite PRN code phase offset is given by

$$\Delta t_{SV} = a_{f0} + a_{f1} t_k$$

The time from epoch t_k is computed as described in Table 2-15, except that t_{oe} is replaced with t_{oa} and the polynomial coefficients a_{f0} and a_{f1} are given in the almanac. Since the periodic relativistic effect is less than 25 meters, it need not be included in the time scale used for almanac evaluation. Over the span of applicability, it is expected that the almanac time parameters will provide a statistical URE component of less than 135 meters, 1σ. This is partially due to the fact that the error caused by the truncation of a_{f0} and a_{f1}, may be as large as 150 meters plus 50 meters/day relative to the t_{oa} reference time.

Acronyms

BIH	BUREAU INTERNATIONAL DE L'HEURE
bps	bits per second
BPSK	Bipolar-Phase Shift Key
C/A	Coarse/Acquisition
CS	Control Segment
dBi	Decibels, isotropic
dBw	Decibels, watt
DN	Day Number
DOD	Department of Defense
DOP	Dilution of Precision
ECEF	Earth-Centered, Earth-Fixed
FOC	Full Operational Capability
GPS	Global Positioning System
HOW	Hand-Over Word
ID	Identification
IOC	Initial Operational Capability
IODC	Issue of Data, Clock
IODE	Issue of Data, Ephemeris
LSB	Least Significant Bit
LSF	Leap Seconds Future
Mbps	Million bits per second
MCS	Master Control Station
MSB	Most Significant Bit
NSC	Non-Standard C/A-Code
NTE	Not-To-Exceed
OCS	Operational Control System
PRN	Pseudo Random Noise
RF	Radio Frequency
RHCP	Right Hand Circularly Polarized
RMS	Root Mean Square
SA	Selective Availability
SS	Space Segment
TLM	Telemetry
TOW	Time of Week
TT&C	Telemetry, Tracking and Commanding

Acronyms (continued)

UE	User Equipment
URA	User Range Accuracy
URE	User Range Error
U.S.	United States
USNO	U.S. Naval Observatory
UTC	Universal Coordinated Time
WGS-84	World Geodetic System 1984
WN	Week Number

GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE SIGNAL SPECIFICATION

ANNEX A

STANDARD POSITIONING SERVICE PERFORMANCE SPECIFICATION

November 5, 1993

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SECTION 1.0 SPS Minimum Performance Standards

This Annex specifies the minimum performance which an SPS user can expect to experience, when equipped with an SPS receiver which is designed and operated in accordance with the SPS Signal Specification. Performance is specified in terms of minimum performance standards for each performance parameter. Each standard includes a definition of conditions and constraints applicable to the provision of the specified service. SPS performance parameters associated with the standards are defined in Section 1.4.2 of the SPS Signal Specification. See Annex B for a more detailed discussion of each performance parameter, and a description of expected SPS performance characteristics. See Annex C for specific information regarding the measurement of performance against each standard.

Any performance parameters not specified in this Annex are not considered to be part of the minimum SPS performance standards, or to represent a part of the minimum service being provided to the civil community.

In the standard definitions below, two terms are used that require clarification: *global average* and *worst-case point*. The definition of a standard in terms of a global average represents a conservative average performance which a user located at any arbitrary location on or near the Earth can expect to experience. The definition of a standard in terms of a worst-case point represents a bound on the performance which a user located at the worst possible location on or near the Earth can expect to experience.

Note that accuracy performance standards are based upon signal-in-space error characteristics and their effects on the position solution. The standards do not include the contribution of the SPS receiver to position error.

SECTION 2.0 Coverage Standard

SPS coverage will be provided in accordance with the following tolerances.

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 obscura • 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 obscura • Standard is predicated on 24 operational satellites, as the constellation is defined in the almanac

SECTION 3.0 Service Availability Standard

SPS service availability will be provided in accordance with the following tolerances.

Service Availability Standard	Conditions and Constraints
≥ 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
≥ 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
≥ 95.87% global average on worst-case day	• Conditioned on coverage standard • Standard represents a worst-case 24 hour interval, averaged over the globe
≥ 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

SECTION 4.0 Service Reliability Standard

SPS service reliability will be provided in accordance with the following tolerances.

Service Reliability Standard	Conditions and Constraints
≥ 99.97% global average	• Conditioned on coverage and service availability standards • 500 meter NTE predictable horizontal error reliability threshold • 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 • 500 meter NTE predictable horizontal error reliability threshold • 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

SECTION 5.0 Positioning and Timing Accuracy Standard

GPS positioning and timing accuracy will be provided in accordance with the following tolerances.

Accuracy Standard	Conditions and Constraints
Predictable Accuracy ≤ 100 meters horizontal error 95% of time ≤ 156 meters vertical error 95% of time ≤ 300 meters horizontal error 99.99% of time ≤ 500 meters vertical error 99.99% of time	• Conditioned on coverage, service availability and service reliability standards • Standard based on a measurement interval of 24 hours, for any point on the globe
Repeatable Accuracy ≤ 141 meters horizontal error 95% of time ≤ 221 meters vertical error 95% of time	• Conditioned on coverage, service availability and service reliability standards • Standard based on a measurement interval of 24 hours, for any point on the globe
Relative Accuracy ≤ 1.0 meters horizontal error 95% of time ≤ 1.5 meters vertical error 95% of time	• Conditioned on coverage, service availability and service reliability standards • Standard based on a measurement interval of 24 hours, for any point on the globe • Standard presumes that the receivers base their position solutions on the same satellites, with position solutions computed at approximately the same time
Time Transfer Accuracy ≤ 340 nanoseconds time transfer error 95% of time	• Conditioned on coverage, service availability and service reliability standards • Standard based upon SPS receiver time as computed using the output of the position solution • Standard based on a measurement interval of 24 hours, for any point on the globe • Standard is defined with respect to Universal Coordinated Time, as it is maintained by the United States Naval Observatory

GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE SIGNAL SPECIFICATION

ANNEX B

STANDARD POSITIONING SERVICE PERFORMANCE CHARACTERISTICS

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SECTION 1.0 Introduction

GPS performance behavior is dynamic, particularly when it is compared with systems such as LORAN-C. The dynamic nature of GPS performance is understandable, given the four-dimensional nature of the position solution and the use of satellites as mobile beacons. GPS performance may however be defined in a straightforward fashion, and bounds or standards placed upon the range of performance a user will experience. These bounds are established in the Annex A as SPS performance standards. The proper context in which to view GPS performance standards is provided through a definition of expected variations for each aspect of system performance.

1.1 Purpose

This Annex defines expected GPS SPS performance parameters and their characteristics, as a function of time, user location, system design and changing operational conditions. This Annex defines the civil GPS performance envelope associated with the minimum performance standards established in Annex A.

1.2 Scope

The data contained in this Annex provides a context for proper understanding and interpretation of civil minimum performance standards established in the GPS SPS Signal Specification. The data and associated statements provided in this Annex represent conservative performance expectations, based upon extensive observations of the system.

The GPS SPS Signal Specification establishes new definitions and relationships between traditional performance parameters such as coverage, service availability, service reliability and accuracy. GPS performance specifications have previously been made to conform to definitions which apply to fixed terrestrial positioning systems. The new definitions are tailored to better represent the performance attributes of a space-based positioning system.

1.3 An Overview of SPS Performance Parameters

System behavior is defined in terms of a series of performance parameters. These parameters are statistical in nature, to better represent performance variations over time. The four performance parameters dealt with in this Annex are: coverage, service availability, service reliability and accuracy, as shown in Figure 1-1. The characteristics of each of these parameters must be considered to completely define the GPS civil performance envelope.

A very important relationship exists between these performance parameters. Performance definition begins with coverage. Each successive layer of performance definitions are conditioned on the preceeding layers. For example, coverage must be provided before the service may be considered available, it must be available before it can support service reliability requirements, and the service must be performing reliably before accuracy standards may be applied.

1.3.1 Coverage

GPS ***coverage*** is viewed somewhat differently than coverage for terrestrial provided 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 SPS receiver generating a marginal position solution. Coverage characteristics over any given region vary slightly over time, due primarily to small shifts in satellite orbits.

COVERAGE

DEFINITION: The percentage of time over a specified time 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.

SERVICE AVAILABILITY

DEFINITION: Given coverage, 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.

SERVICE RELIABILITY

DEFINITION: Given coverage and service availability, the percentage of time over a specified time interval that the instantaneous predictable horizontal error is maintained within a specified reliability threshold at any point on or near the Earth.

ACCURACY

DEFINITION: Given coverage, service availability and service reliability, the percentage of time over a specified time interval that the difference between the measured and expected user position or time is within a specified tolerance at any point on or near the Earth.

Figure 1-1. GPS Performance Parameters

1.3.2 Service Availability

Just because a satellite is operational does not mean that it is currently transmitting a usable SPS 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.

1.3.3 Service Reliability

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 a specified reliability error threshold. 100% service reliability is provided when the horizontal error does not exceed the reliability error threshold, 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.

GPS service reliability is a function of several factors. The primary factors are the failure frequency, and duration of the SPS ranging signal service. Once a ranging signal service failure has occurred, the probability that a user at any arbitrary location will experience a reliability failure due to the service failure depends on:

- The user's location relative to the failed satellite's coverage pattern,
- The amount of time that the failed satellite is in view if the user is within some portion of the coverage pattern,
- The probability that the user will use the failed satellite in the position solution, and
- The probability that the magnitude of the failure will be large enough to induce a service reliability failure, based upon the specific solution geometry through which the error is being mapped.

1.3.4 Accuracy

Given that coverage is provided, the service is available and all satellites are performing within reliability tolerances, GPS position solution ***accuracy*** represents how consistently the receiver's output conforms to an expected solution. Users view accuracy in many different ways, depending on their application. To accommodate the majority of users' needs, GPS accuracy is defined in the Signal Specification from four different perspectives:

- Predictable Accuracy,
- Repeatable Accuracy,
- Relative Accuracy, and
- Time Transfer Accuracy.

Each of these aspects of GPS accuracy are described in more detail below. Figure 1-2 compares and contrasts the four different ways of viewing GPS accuracy as it is defined in the Signal Specification.

Predictable accuracy represents how well the position solution conforms to "truth". Truth is defined to be any specified user location where the position is surveyed with respect to an accepted coordinate system, such as the World Geodetic System 1984 (WGS-84) Earth-Centered, Earth-Fixed (ECEF) Coordinate System. GPS was implemented to specifications that are stated in terms of predictable accuracy. Predictable accuracy is a measure used by those who are concerned with how well they can position themselves relative to a known, surveyed location. Factors which affect predictable accuracy include geometry variations unique to a given user location, and the sample interval over which measurements are taken.

Repeatable accuracy is a measure of position solution consistency relative to a user's previous position solution. Users who are interested in returning to points where they previously used GPS to determine their position will rely upon GPS repeatable accuracy performance. Repeatable accuracy varies primarily as a function of time between measurements.

Relative accuracy is a measure of the correlation in the errors between position solutions from two different receivers, using the same satellites at approximately the same time. Users who wish to locate other receivers relative to their location are most concerned with relative accuracy. Ideally, only very small differences will exist between the position solutions of two receivers that are relatively close together and consistently use the same satellites. These differences will be due primarily to receiver designs and measurement noise plus the difference in solution generation times. Other factors which can potentially contribute relative solution errors are slight differences in solution geometries and ranging errors between the two sites. These factors provide a negligible contribution to relative errors, as long as the receivers are within 40 kilometers of each other. The 40 kilometer constraint is based simply on the fact that it becomes increasingly difficult beyond that distance to base the two position solutions on common-view satellites that provide a position solution geometry within Position Dilution of Precision (PDOP) constraints.

Time transfer accuracy defines how well a position service user can relate receiver time to Universal Coordinated Time (UTC) as it is disseminated by the United States Naval Observatory (USNO).

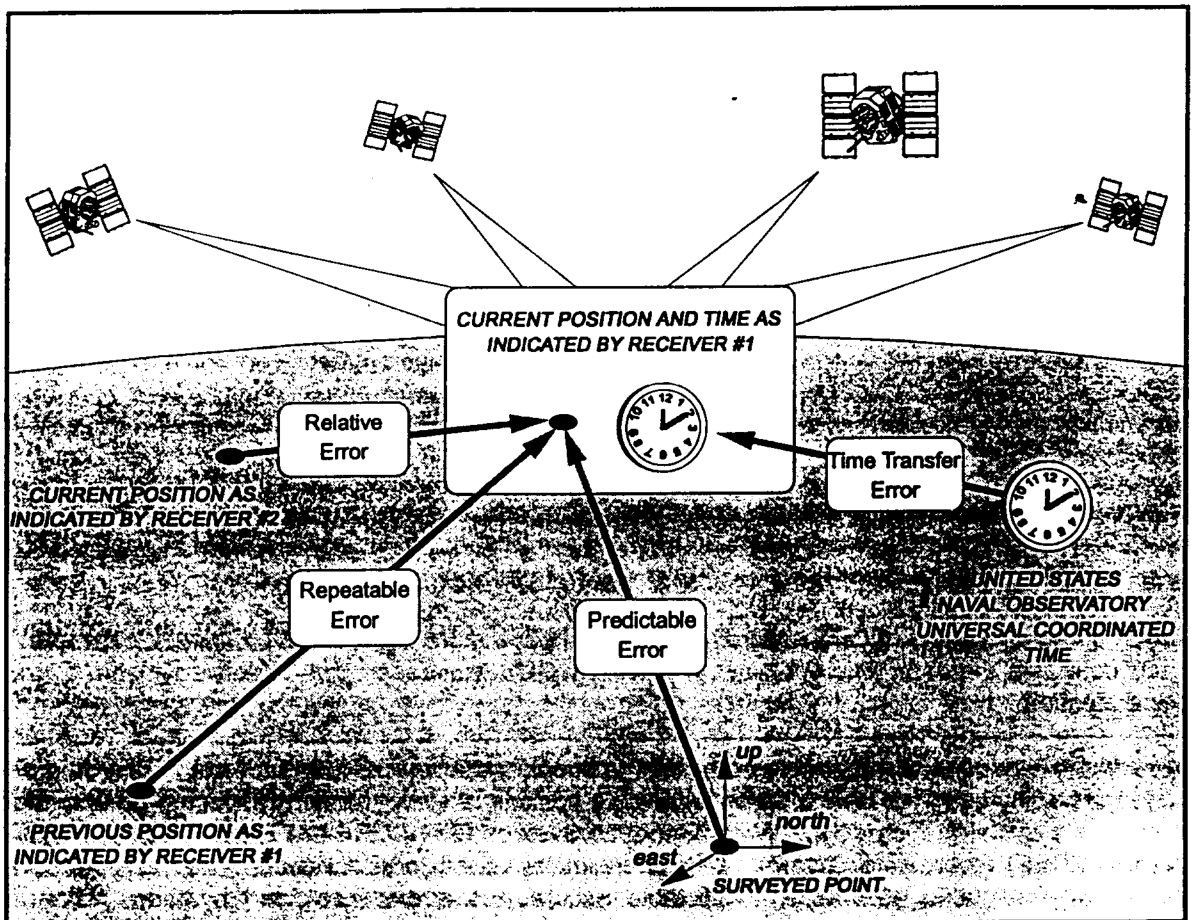

Figure 1-2. The Different Aspects of GPS Accuracy

1.4 Key Terms and Definitions

The terms and definitions of technical concepts provided below should be reviewed to ensure a common understanding of the material presented in this Annex.

Measurement Samples. A group of measured quantities that meet random sampling criteria when they are taken from a specified population. Each of the measured quantities are explicitly grouped by a specified measurement process and by the measurement interval over which the measurements were taken.

Measurement Interval. The time interval over which measurement samples are gathered from a specified population to evaluate an aspect of system performance.

Stationarity. A measure of statistical behavior consistency over successive sample intervals for a specified sample population. Individual satellite ranging errors which provide consistent mean and variance statistics over successive sample intervals may be viewed as being sufficiently stationary. This specific view of stationarity is also known as *wide-sense stationarity*.

Ergodicity. The degree to which the statistical behavior of instantaneous samples from several populations conform to the statistical behavior of samples from one population over a sample interval. A series of satellites with similar and stationary ranging error statistics over successive sample intervals may be viewed as behaving in an approximately ergodic manner.

Steady-State. Behavior within statistical expectations.

Transient. Short term behavior not consistent with steady-state expectations.

Position Solution Geometry. The set of direction cosines which define the instantaneous relationship of each satellite's ranging signal vector to each of the position solution coordinate axes.

Dilution of Precision (DOP). A Root Mean Square (RMS) measure of the effects that any given position solution geometry has on position errors. Geometry effects may be assessed in the local horizontal (HDOP), local vertical (VDOP), three-dimensional position (PDOP), or time (TDOP) for example.

User Navigation Error (UNE). Given a sufficiently stationary and ergodic satellite constellation ranging error behavior over a minimum number of measurement intervals, multiplication of the DOP and a constellation ranging error standard deviation value will yield an approximation of the RMS position error. This RMS approximation is known as the UNE (UHNE for horizontal, UVNE for vertical, and so on). The user is cautioned that any divergence away from the stationary and ergodic assumption will cause the UNE to diverge from a measured RMS value.

SECTION 2.0 Coverage Characteristics

This section defines 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.

2.1 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:

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

2) Minimize coverage sensitivity to expected satellite orbital drift characteristics.

3) 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 stationkeeping maneuvers.

2.2 Expected Coverage Characteristics

Proper support of Design Objective 1 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 2-1, 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 6.

Unfortunately, variations in final orbits based upon launch uncertainties and routine drift do occur. Design Objective 2 is supported by evaluating how changes in each satellite's orbital elements affect nominal coverage characteristics. Bounds are applied to orbital element deviations 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°), 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°.

Satisfaction of Design Objective 3 requires that we be able 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 2-1, 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.

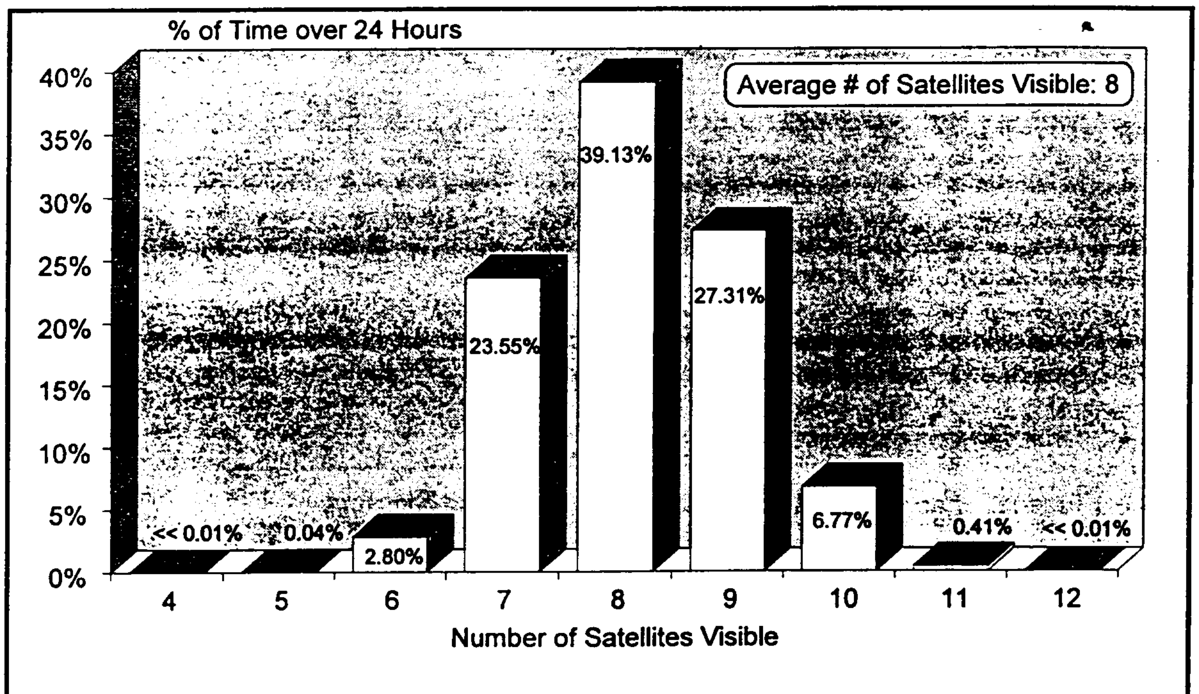

Figure 2-1. Satellite Global Visibility Profile

A final point on coverage performance relates to the term "on or near the Earth" used throughout the Signal Specification. Since GPS is a space-based system, coverage is defined as a function of each satellite's navigation signal beamwidth. The GPS satellite's nominal beamwidth is approximately ±14.3°. 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".

SECTION 3.0 Service Availability Characteristics

This section defines 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.

3.1 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 groundrule 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 3-1.

Table 3-1. 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%	100%
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%

3.2 Expected Service Availability Characteristics

Table 3-1 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 3-1 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 3-2. 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 experience downtime. The service availability service standard was established based upon this scenario, to ensure that the system can support standard compliance.

Table 3-2. Example of 30-Day Global Service Availability with Component Failure on Worst Day

Ops Scenario Condition	Best Case	Average Case	Worst Case
1 Day - 3 satellites down	0.9989	0.9903	0.9587
1 Day - 1 satellite down	0.9998	0.9993	0.9983
28 Days - No satellites down	1.0	1.0	1.0
Average Daily Availability	99.99%	99.97%	99.85%

The second service availability scenario is shown in Table 3-3, 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 3-3. Example of 30-Day Global Service Availability without Component Failure

Ops Scenario Condition	Best Case	Average Case	Worst Case
3 Days - 1 satellite down	0.9998	0.9993	0.9985
27 Days - No satellites down	1.0	1.0	1.0
Average Daily Availability	99.99%	99.99%	99.98%

SECTION 4.0 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.

4.1 Reliability Threshold Selection

As defined in Section 1.3, service reliability is the measure of how consistently GPS horizontal error levels can be maintained below a specified reliability threshold. The selection of an appropriate value for this threshold is based upon an assessment of normal accuracy characteristics. A description of normal accuracy characteristics is provided in Section 5.2, which contains expected error statistic variations and distributions. The value must be larger than the practical limit on normal GPS horizontal performance. The largest horizontal error that can be experienced under normal operating conditions, with a PDOP constraint of 6, is approximately 400 meters. A value of 500 meters was chosen as the reliability threshold because it is sufficiently outside the normal GPS SPS accuracy envelope to avoid a false alarm condition, and because it should serve as a usable input to aviation plans for phases of flight down to terminal area operations.

Given a horizontal error reliability threshold, a corresponding Not-To-Exceed (NTE) ranging error threshold may be defined that bounds the SPS horizontal error within the specified threshold for a specified range of position solution geometries. A ranging error threshold is used in the service failure detection process as opposed to a position error threshold, due to the practical difficulties associated with monitoring position solutions on a global basis. A ranging error threshold of 150 meters will provide a 500 meter bound on the maximum predictable horizontal error, given a maximum Horizontal Dilution of Precision (HDOP) of 4.

4.2 GPS Service Failure Characteristics

A service failure is defined to be a condition where the positioning service is exhibiting time ordered error behavior which is atypical. An occurrence of this behavior is directly due to a failure somewhere in the GPS ranging signal control and generation process.

Service failures are classified into two categories: minor and major. A minor service failure is defined to be a departure from the normal ranging signal characteristics in one of the following ways:

- A statistical departure from nominal system ranging accuracy which does not cause the instantaneous SPS ranging error to exceed 150 meters.

- A navigation message structure or content violation which does not impact the minimum SPS receiver's navigation message processing capabilities.

A major service failure is defined to be a departure from the normal ranging signal characteristics in a manner which can cause a reliability or availability service failure. A major service failure is defined to be a departure from the normal ranging signal characteristics in one of the following ways:

- A statistical departure from nominal system ranging accuracy which causes the SPS instantaneous ranging error to exceed 150 meters, or
- An SPS ranging signal RF characteristic, navigation message structure or navigation message contents violation that impacts the SPS receiver's minimum ranging signal reception or processing capabilities.

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.

4.2.1 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.

4.2.2 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.

4.2.3 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 manifest themselves) 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 SPS 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 meters 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.

4.2.4 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.

4.2.5 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 2-1. 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.

4.2.6 Failure Effect on Position Solution

Given the nature of catastrophic failures, it must be assumed that the inclusion of a 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 SPS 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.

4.3 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%.

SECTION 5.0 Accuracy Characteristics

This section describes GPS position solution time ordered behavior, and defines expected error statistic characteristics for four different aspects of accuracy: predictable, repeatable, relative and time transfer. The user is provided with information describing GPS accuracy daily variations and accuracy as a function of user location.

One of the underlying assumptions implicit in the definition of the accuracy performance envelope is that satellite ranging error statistics across the constellation are approximately ergodic. In reality, this may not be the case for several reasons. Regardless of the variations in ranging performance across the constellation, positioning and timing performance will be no worse than it is represented by the accuracy performance standards.

5.1 Positioning Error Time Ordered Behavior

Unlike a system such as LORAN-C, GPS position solution errors change considerably over time at any given location. Figure 5-1 demonstrates typical position solution horizontal coordinate changes from minute-to-minute over a one-hour interval, as they would be seen by a user located at the coordinate crosshairs. Based upon observed system behavior, the horizontal position estimate shifts about one meter every second on average. A statistical behavior pattern begins to emerge when the observation window is widened to 24 hours (the sample interval specified in the accuracy performance standard). As shown in Figure 5-2, horizontal errors are grouped about the coordinate origin, with a few outliers near and beyond the 95% performance standard circle. Excursions beyond the 100-meter circle are infrequent, and they seldom last more than a minute.

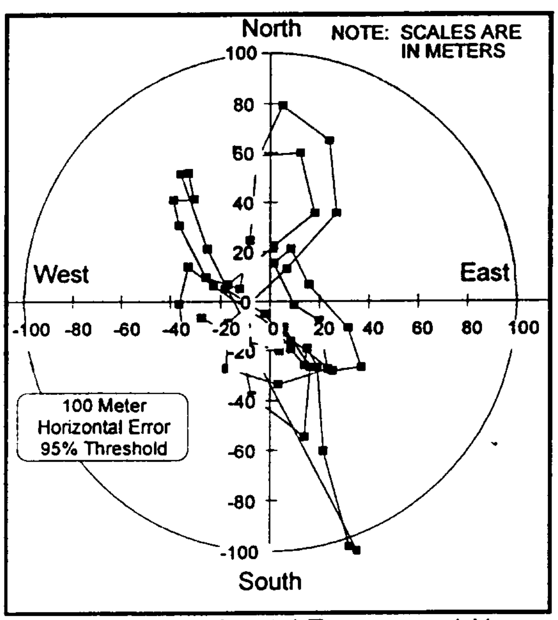

Figure 5-1. Horizontal Errors over 1 Hour

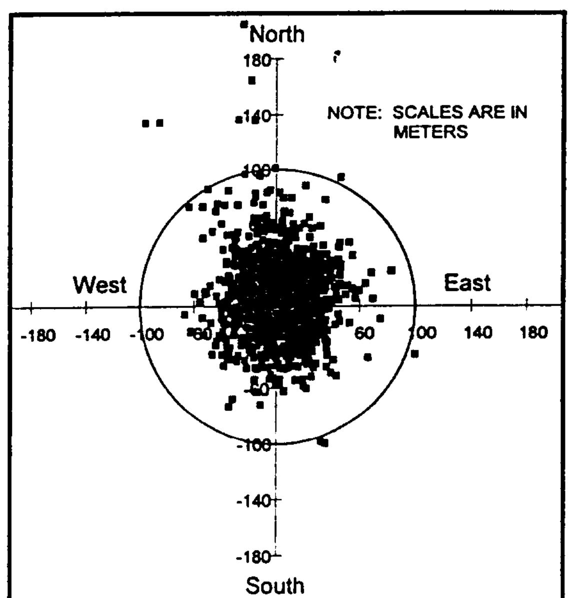

Figure 5-2. Horizontal Errors over 24 Hours

Changes in vertical coordinate estimates are generally larger than those in the horizontal plane, due to the nature of the position solution geometry. Figure 5-3 provides an example of how vertical errors change from minute-to-minute over a one-hour interval. Based on observed system behavior, the vertical position estimate shifts about 1.5 meters every second on average. The 24-hour plot of vertical errors in Figure 5-4 show grouping about a zero mean (approximately), with few deviations beyond the 156 meter line.

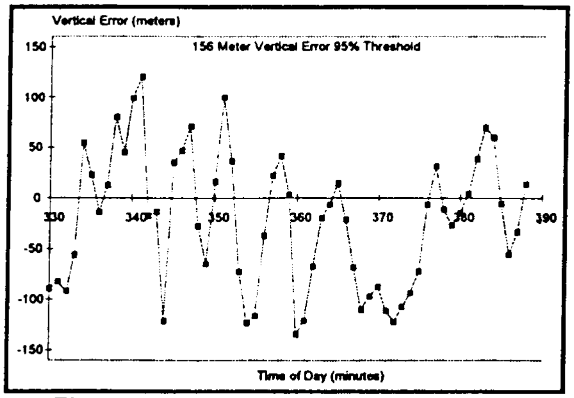

Figure 5-3. Vertical Errors over 1 Hour

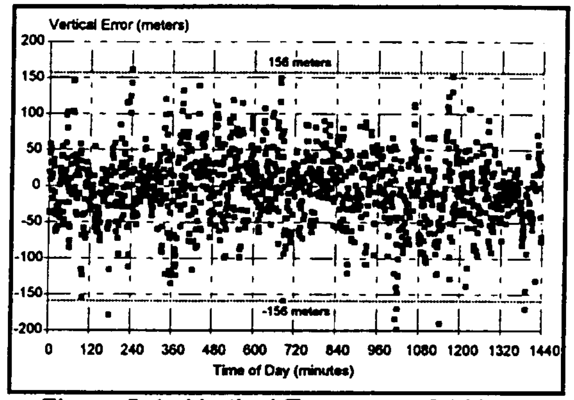

Figure 5-4. Vertical Errors over 24 Hours

Instantaneous position estimate changes, on the order of tens of meters, may be observed at times during a transition between satellites used in the position solution. This transient behavior is due to an abrupt change in solution geometry, combined with differences in ranging errors between the old and new satellite(s). On those occasions where several large jumps in the position solution are observed over the course of a few minutes, this behavior is probably due to multiple changes in the receiver's satellite selection.

5.2 Predictable Accuracy Characteristics

As mentioned in Section 1.3.4 of this Annex, predictable accuracy statistics vary as a function of sample interval and user location. The following discussions focus on both of these factors, and their implications on the ability of GPS to support SPS predictable accuracy requirements. The discussion concludes with a description of expected GPS SPS predictable accuracy distribution characteristics.

5.2.1 Daily Variations in Positioning Errors

GPS accuracy requirements are stated in terms of 24-hour measurement intervals. Even in steady-state operations however, the full range of GPS position error behavior can not be experienced over 24 hours at any given site. As a result, error statistics over any set of 24-hour intervals will vary. Measured average daily variations of GPS 24-hour 95% error statistics over 30 days of steady-state operations are as follows:

- East: 15%
- North: 14%
- Vertical: 10%
- Horizontal: 10%

In the event that ranging error statistical behavior changes for one or more satellites over a given interval, larger variations than those listed above may be observed by the user.

5.2.2 Geographic Variations in Positioning Errors

GPS predictable accuracy performance is specified in terms of global horizontal and vertical errors over 24 hours for any location on or near the Earth. Performance will however vary considerably as a function of user location. The purpose of the following discussion is to characterize how GPS predictable accuracy varies as a function of user latitude and longitude. Stated values will hold true for steady-state constellation operations, with all satellites providing similar range error characteristics. Error estimates are based upon 24-hour measurement intervals, with at least 30 days of steady-state operations. Figure 5-5 provides a summary of GPS performance variation as a function of user latitude.

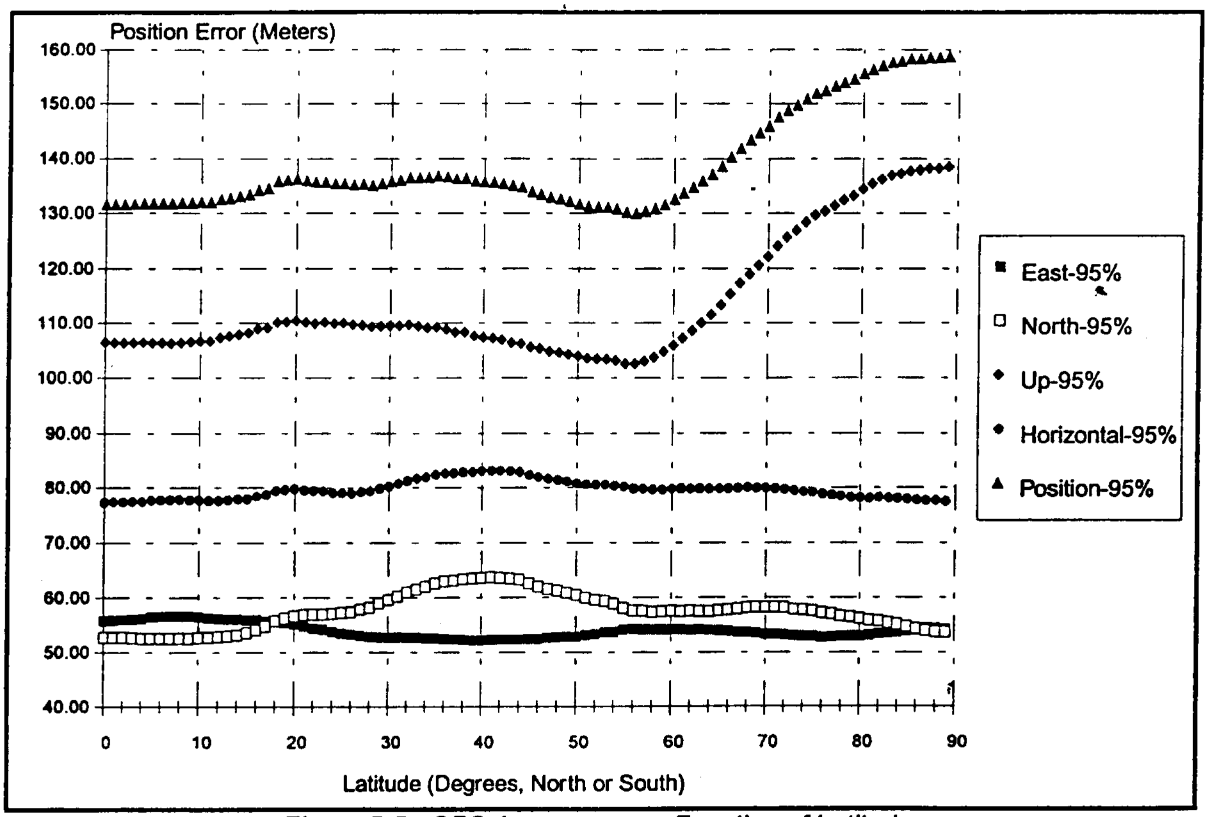

Figure 5-5. GPS Accuracy as a Function of Latitude

Due to the nature of the satellite constellation design, GPS exhibits hemispherical symmetries in coverage and accuracy attributes. GPS error behavior is approximately symmetric between the Northern and Southern hemispheres. GPS latitude-dependent errors for any given longitude in the Southern Hemisphere are phased 90 degrees with respect to Northern Hemisphere longitudinal error characteristics. GPS longitude-dependent errors in any half of a hemisphere (North or South) are approximately symmetric with the other half of the same hemisphere.

Average longitudinal variations in east, north, and vertical 95% errors are less than 5% for any given latitude (excluding transient areas of degraded coverage). Average longitudinal variations in horizontal and (three-dimensional, or 3D) position 95% errors for any given latitude are less than 2% (excluding transient areas of degraded coverage). Degraded coverage areas will cause spikes in the latitude-dependent error curve. The magnitude of a spike depends on the service availability characteristics for the time interval of interest. Given that all 24 satellites are available, the largest expected growth in north, east or horizontal 24 hour 95% error values for a site affected by degraded coverage is 12% above the nominal value for that latitude (given a PDOP constraint of 6). Vertical and 3D position 95% error values can increase by as much as 31% for those areas affected by a coverage degradation (once again, given a PDOP constraint of 6).

Given the coverage and service availability characteristics discussed in Sections 2 and 3, these degradation areas are not expected to occur very often.

North errors vary considerably more as a function of latitude than do east errors. 95% east errors are generally larger than 95% north errors between ± 18° latitude. After 18°, the north error statistic can become as much as 22% larger than the east error statistic. Vertical error grows 3% between 0° and ± 21° latitude, gradually decreases 7% between 20° and 56°, and then grows 35% between 56° and 90°. This growth behavior after 56° is due to the fact that the maximum satellite elevation angle decreases steadily as latitude increases beyond the nominal satellite orbit inclination of 55°.

Horizontal error grows 7.5% between 0° and ± 43° degrees latitude, and then gradually decreases 7.2% between 43° and 90°. 3D position error statistics follow the same general trend as vertical error statistics, due to vertical error dominance and almost constant horizontal error behavior as a function of latitude.

5.2.3 Expected Error Distribution Characteristics

Error distributions provide a convenient means of summarizing predictable accuracy characteristics. However, the definition of any GPS position error distribution must be caveated with the fact that performance varies as a function of sample interval and location, as was discussed in the preceding sections. The error distributions provided in this section are based upon measured data from the GPS Control Segment monitor stations. These monitor stations are in general located close to the equator, so the local axis error distributions will deviate from their representation in Figure 5-6 as user latitude increases. The horizontal error distribution shown in Figure 5-7 is fairly representative of expected performance, irregardless of latitude. The distributions in Figures 5-6 and 5-7 are all generated using three months' worth of data, so a user can expect to see daily variations with respect to these distributions in accordance with the discussion in Section 5.2.1.

The empirical error distributions are overlaid with Gaussian distributions, as a basis for comparison with theoretical expectations. The theoretical distributions were generated using the means and standard deviations of the empirical datasets.

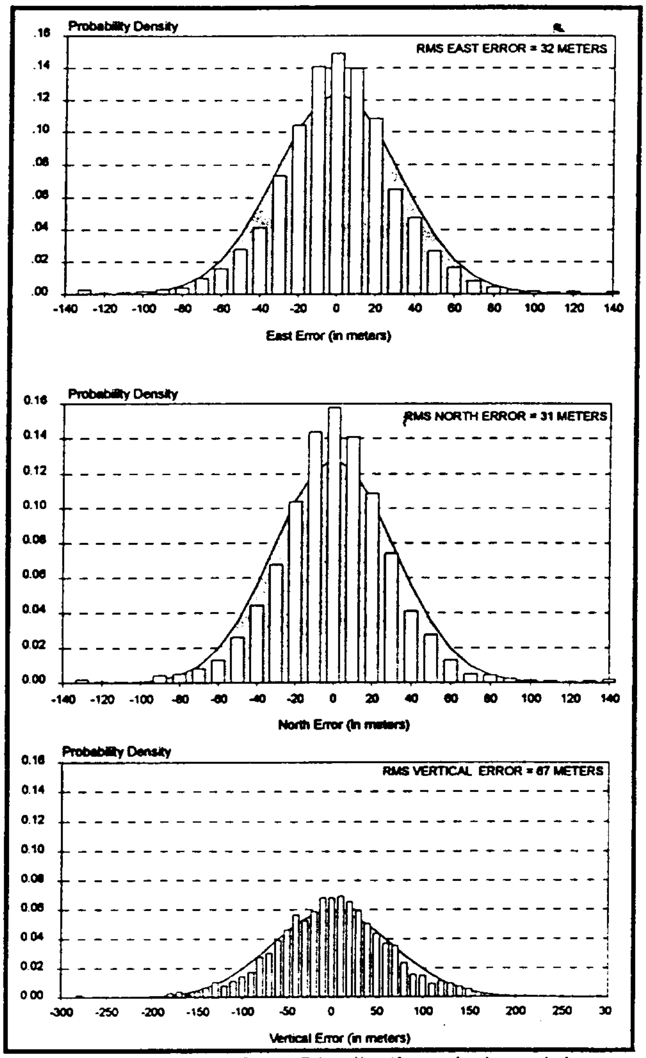

Figure 5-6. SPS Error Distributions in Local Axes

Annex A to the SPS Signal Specification establishes additional predictable accuracy standards of 300 meters horizontal error and 500 meters vertical error, both with a 99.99% confidence over any

24 hour interval, at any given location in the world. Based upon observed distribution characteristics, these standards will be met as long as the system does not experience a service failure.

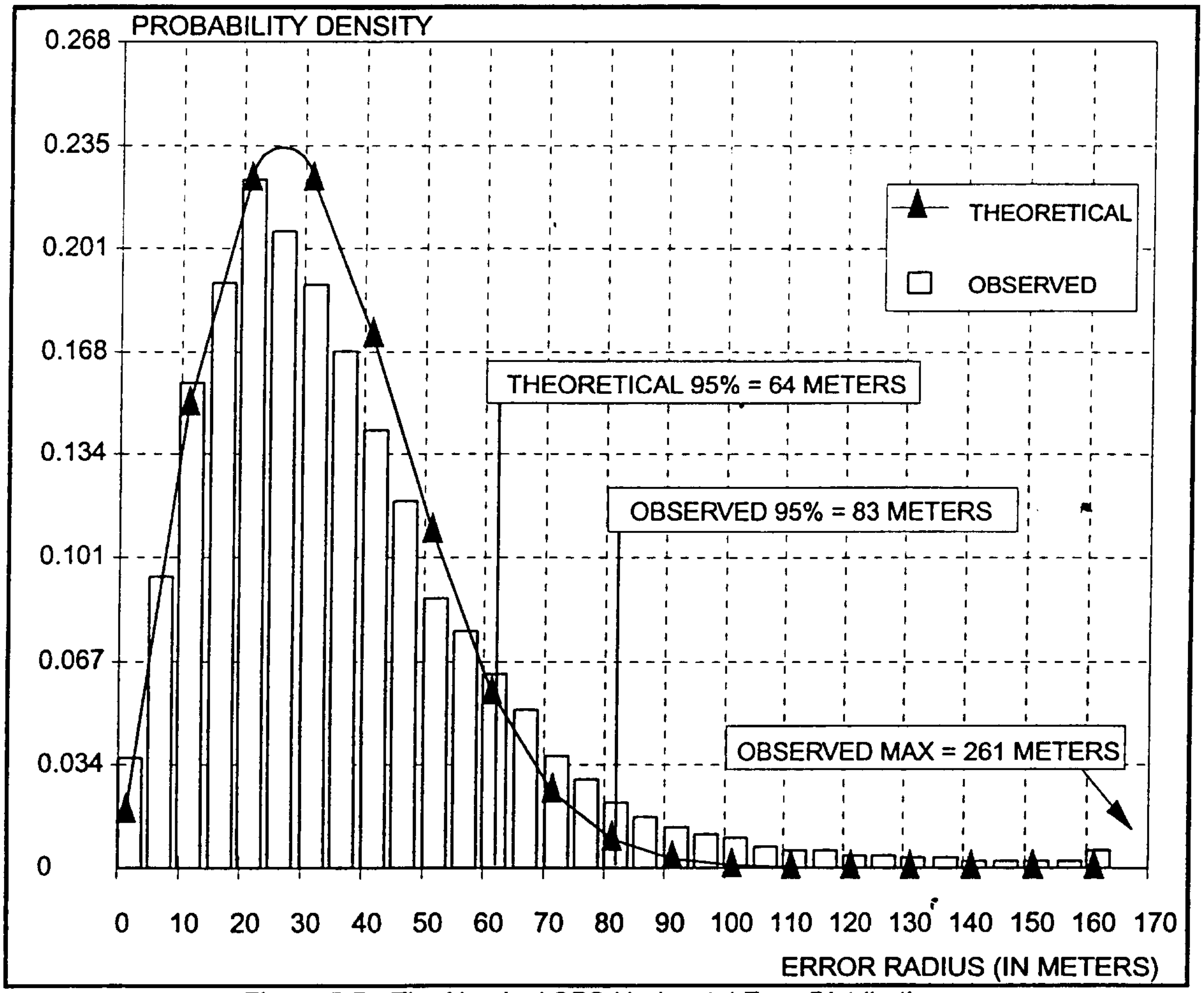

Figure 5-7. The Nominal SPS Horizontal Error Distribution

5.3 Repeatable Accuracy Characteristics

Repeatable accuracy statistics vary primarily as a function of the time between position measurements. The error in general grows as the time between measurements increases, until the interval reaches approximately 4 minutes. After 4 minutes, the repeatable error statistics are essentially independent of time between measurements. This behavior is reflected in Figure 5-7, where the RMS horizontal repeatable error grows to approximately 53 meters before its behavior stabilizes. Horizontal 95% repeatable accuracy is on the order of 105 meters, and vertical 95% repeatable accuracy is on the order of 165 meters at the equator. Based upon this performance, repeatable accuracy performance will remain within the performance standards, irrespective of daily or geographic variations.

5.4 Relative Accuracy Characteristics

The graph in Figure 5-9 below shows how errors in the measurement of the relative vector between two receivers tracking the same satellites grow, as a function of time between the two

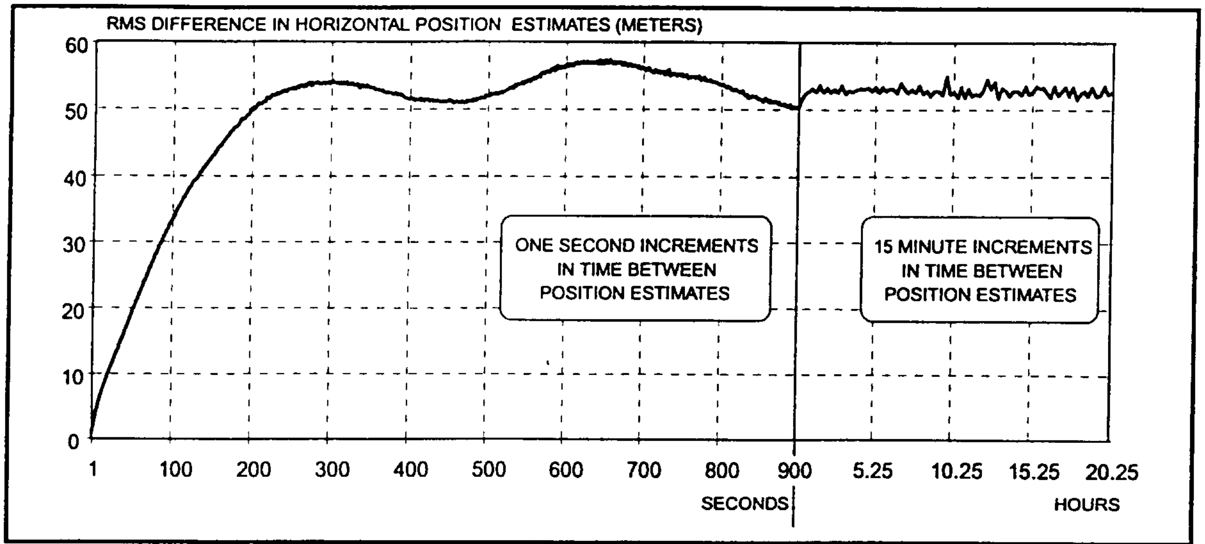

Figure 5-8. Repeatable Accuracy as a Function of Time between Position Estimates

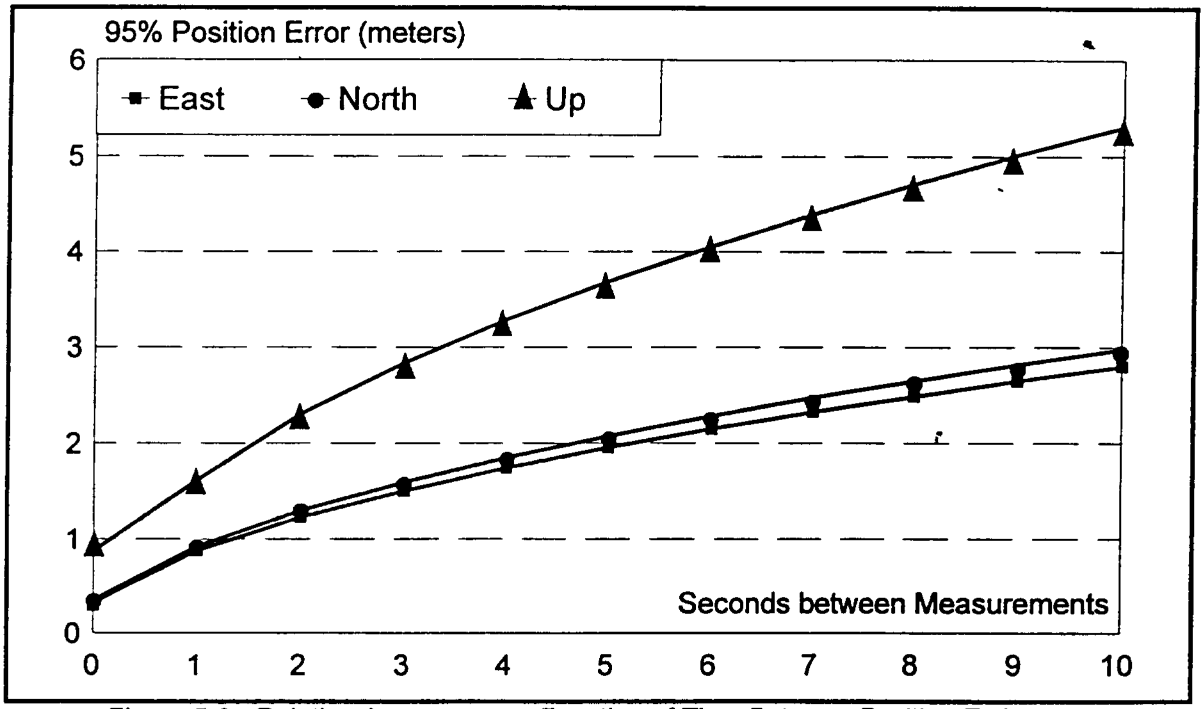

Figure 5-9. Relative Accuracy as a Function of Time Between Position Estimates

receivers' measurements. The receivers must be within 40 kilometers of each other, in order to experience performance consistent with the performance standard. The 40 kilometer value is considered to be a practical limit on the distance between receivers for relative positioning implementations, based upon a strict conformance with the relative positioning definition and performance standard values established in the Signal Specification. The limit is based upon the fact that satellite tracking coordination to support optimum position solution geometries (PDOP $\leq$ 6) becomes increasingly difficult for receivers further than 40 kilometers apart.

Users need to be aware of the fact that the accuracy performance standards are based upon signal-in-space error characteristics, and do not take into consideration receiver contributions to error statistics. The other aspects of accuracy are not affected by this distinction in a practical sense, since the receiver error contribution is very small relative to the signal-in-space error. In the case of relative accuracy however, receiver noise characteristics become the dominant error source. User relative accuracy performance will depend significantly on consistency in the two receivers' designs, and coordination of position solution satellite selection and generation timing. Users may experience performance which is consistent with Figure 5-9, or 95% horizontal relative accuracies as large as 6 meters and 95% vertical relative accuracies as large as 9 meters depending on the receivers used.

5.5 Time Transfer Accuracy Characteristics

Time transfer accuracy based upon the output of the position solution is a function of SPS timing errors with respect to GPS time, and GPS time scale errors with respect to Universal Coordinated Time (UTC) as it is maintained by the United States Naval Observatory. Current satellite SPS timing errors with respect to GPS time are on the order of 75 nanoseconds RMS (including propagation effects). The GPS Control Segment consistently manages GPS time coordination with UTC to better than 30 nanoseconds.

When the combined GPS time prediction error and GPS-UTC time synchronization errors are mapped into the position solution, the RMS time transfer error is on the order of 110 ns. The 95% UTC time transfer error should not exceed 250 nanoseconds, based upon measurements of the position solution time offset. The 340 nanosecond performance standard defined in Annex A provides the Control Segment with flexibility in the management of the GPS time scale.

GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE SIGNAL SPECIFICATION

ANNEX C

MEANS OF MEASURING GPS PERFORMANCE

November 5, 1993

TABLE OF CONTENTS

SECTION 1.0 Introduction

Performance standards can not be considered to be valid unless they are quantifiable, and the ability of GPS to meet them can be consistently measured. The first criteria is met with the specific definitions contained in Annex A, of GPS performance standards and the conditions under which they will be met. The ability to meet the second criteria, to consistently measure GPS performance, depends upon the establishment of methodologies which can be universally applied to the performance evaluation process.

1.1 Purpose

The purpose of this Annex is to define measurement methodologies for evaluating GPS performance against the established performance standards. The measurement methodologies defined in this Annex consist of three parts: measurement groundrules, minimum equipment requirements, and measurement algorithms.

1.2 Scope

The measurement methodologies are designed specifically to assess performance in a manner which is consistent with the performance standards defined in Annex A. The methodologies do not address any aspects of performance beyond those established by the performance standards.

Performance measurement processes defined in this Annex are restricted to individual site performance assessments. The single point performance standards are the success criteria for each assessment. The global performance standards represent conservative average performance values for any arbitrary point on or near the surface of the Earth. In this capacity, the civil user can apply the global performance standards to provide an indication of GPS performance relative to an "average" location.

The methodologies defined in this Annex support general positioning and timing performance measurements against the performance standards. The algorithms provided in this Annex may not be suitable for use with more specific applications of the SPS, such as surveying or differential GPS operations.

Note that all measurement algorithms were developed based upon the spherical Earth assumption. A tradeoff was made in the algorithm designs, between algorithm complexity and a degradation in precision. The spherical Earth algorithms are simple to implement, and provide a minimal degradation in generic position error measurement precision, particularly when compared to the magnitude of the measurements being processed. Application of these algorithms will result in position error measurements which vary less than 0.4% with respect to results obtained using an oblate Earth model. Users who are concerned with measuring GPS performance for applications beyond the scope of this Signal Specification may find that they require the additional precision which more sophisticated algorithms will provide.

The user is cautioned not to apply these algorithms within approximately 100 kilometers of the North or South poles, without making provisions to support the special case of polar measurements.

GPS measurement methodologies are defined using the metric system. Angular quantities are expressed in degrees.

Error distribution generation is not explicitly addressed, nor are distribution characteristics specified in the measurement methodologies. However, any desired empirical accuracy distribution is easily generated from the raw measurement data by sequentially sorting and binning the data in appropriately sized bins.

1.3 References

The following references were used in the development of the GPS performance measurement methodologies:

- *Department of Defense World Geodetic System 1984, Its Definition and Relationships with Local Geodetic Systems*, DMA Publication TR-8350.2 (unlimited distribution), September 30, 1987.

- Clyde R. Greenwalt and Melvin E. Shultz, *Principles of Error Theory and Cartographic Applications*, United States Air Force Aeronautical Chart and Information Center Publication ACIC Technical Report No. 96 (unlimited distribution), February 1962.

- Gerald J. Hahn and William Q. Meeker, *Statistical Intervals: A Guide For Practitioners* (New York: John Wiley & Sons, Inc., a Wiley-Interscience Publication, 1991).

SECTION 2.0 Performance Measurement Groundrules

This section defines groundrules for measuring and evaluating any aspect of GPS performance against the performance standards. Failure to follow the groundrules may lead to erroneous performance measurement results.

GROUNDRULE 1: All performance measures are defined with respect to the WGS-84 ellipsoid and associated ECEF coordinate systems. Errors with respect to the geoid, other ellipsoids and their associated terrestrial coordinate systems, or with respect to terrain features are not defined.

GROUNDRULE 2: Methodologies do not take into consideration the effects of local obscura above specified mask angles.

GROUNDRULE 3: Methodologies are designed to measure GPS SPS positioning performance. Methodologies therefore consider nominal assumed GPS receiver characteristics as they are defined in the Signal Specification central document. The effects of aiding or augmentations to the basic GPS signal are not considered.

GROUNDRULE 4: To simplify algorithm usage, all measurement methodologies use a one-second interval between samples. Maximum intervals between measurements for each performance parameter are provided below, for those who wish to reduce sample rates to minimize data processing and storage requirements. If the sample rate is reduced for an algorithm which provides an input to another algorithm, use the previous measurement value until the next sample. For example, if the service availability sample interval is increased to 30 seconds, use the previous service availability measurement to support service reliability measurements until the next service availability measurement.

Table 2-1. Maximum Intervals between Samples

Performance Parameter	Maximum Interval between Samples
Coverage	30 Seconds
Service Availability	30 Seconds
Service Reliability	Four Seconds
Accuracy - 95% Confidence Interval	60 Seconds
Accuracy - 99.99% Confidence Interval	Four Seconds

GROUNDRULE 5: To ensure consistency in comparisons of results between measurements taken by independent groups, sample collection start time in methodologies is defined to be 0000Z. Since performance requirements are not stated in terms of specific measurement interval start and stop times, start times other than 0000Z may be used at the convenience of users who are not concerned with performance comparisons.

GROUNDRULE 6: In general, assume that at least 90% of the available data points must be collected over the sample interval to provide a representative performance assessment for a given parameter.

GROUNDRULE 7: To ensure that GPS civil performance measurement datasets are consistent with performance standard definitions, all measurements must be taken using a system which meets the minimum requirements for a *GPS Measurement System*. Measurements taken using a system which does not meet the minimum requirements may not support representative system performance evaluations.

SECTION 3.0 Measurement System Minimum Requirements

Standardized measurement methodologies require a minimum set of measurement capabilities. A system which provides these minimum capabilities is referred to as a ***Measurement System***. This section defines the minimum requirements for establishing a Measurement System.

3.1 Measurement System Configurations

Three different types of generic Measurement Systems are defined, to support varying performance measurement needs. Each type requires a successively more sophisticated configuration.

- Measurement System Type 1: Coverage and Availability Measurement
- Measurement System Type 2: Position Accuracy and Service Reliability Measurement
- Measurement System Type 3: Time Transfer Measurement

Figure 3-1 below illustrates an example configuration of a Type 3 Measurement System.

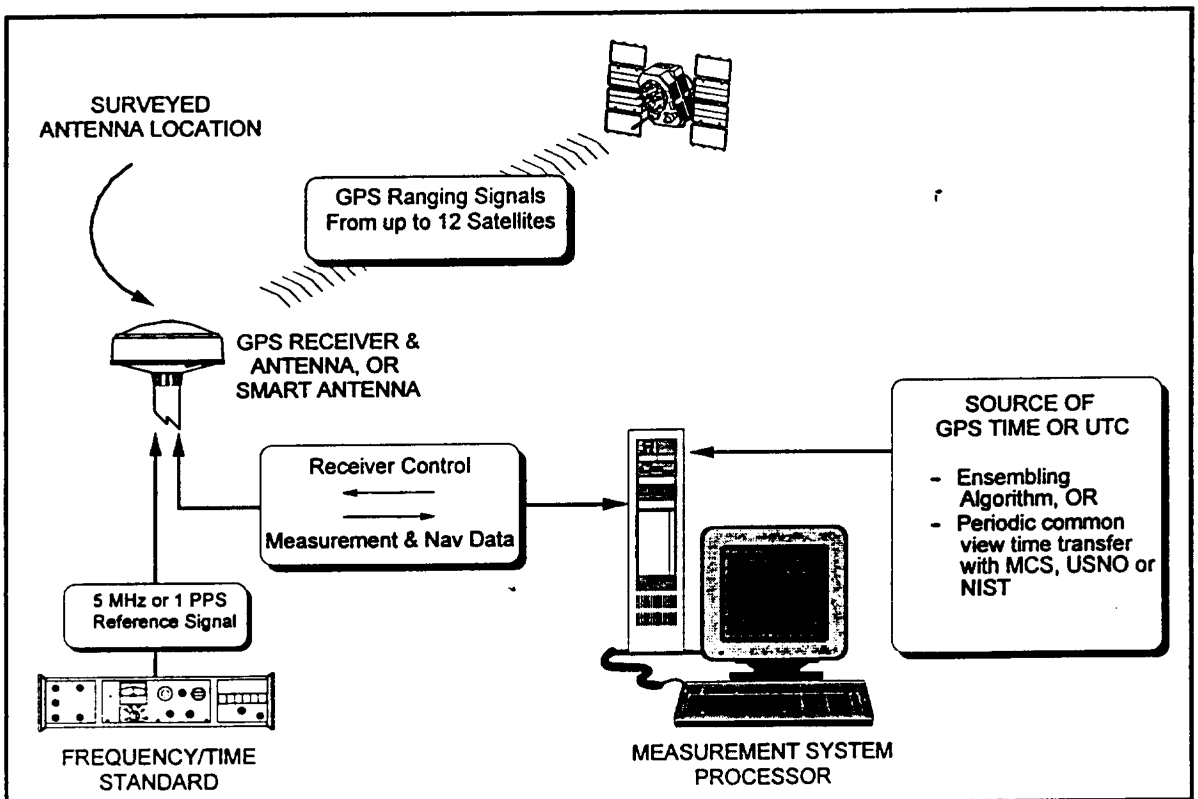

Figure 3-1. Example of Type 3 Measurement System Configuration

Measurement System Type 1 requires that an SPS positioning receiver be tied to a Measurement System processor. The processor controls the receiver configuration, and receives and processes measurement and navigation message data coming from the receiver.

Measurement System Type 2 has the same configuration as Type 1, with the addition of placing the receiver antenna on a surveyed benchmark.

Measurement System Type 3 has the same configuration as Type 2, with the following additions:

- A frequency/time standard to drive receiver range measurement time tags, and
- A mechanism, algorithm or process to synchronize Measurement System time with GPS time and/or UTC.

3.1.1 The Measurement System Processor

The Measurement System processor must support the following functions:

- Receiver control message generation/transmission.
- Measurement and navigation message data reception.
- Generation of raw data files containing performance standard measurement data.

Performance measurement processing can be conducted on the processor, or raw data may be exported for computations on an external processor.

The Measurement System processor supports coverage and availability measurements in the following fashion:

- Generate satellite visibility files as a function of time and mask angle based upon the transmitted almanac.
- Compute the optimum solution geometry based upon the minimum PDOP.
- Read the ephemeris for each of the selected satellites. Check satellite health and for the presence of any flags indicating that the satellite should not be used; if a satellite is unhealthy, update availability files to reflect satellite status, and recompute the optimum solution geometry.

The Measurement System processor supports predictable accuracy and reliability measurements by computing position errors with respect to the surveyed benchmark. Repeatable accuracy measurements are supported through the differencing of position or predictable error vectors. Relative error measurements are supported through the use of two Measurement Systems, or two receivers tied to the same Measurement System. Time transfer error measurements are supported by using a time source tied to UTC as the timing input to the position solution process.

3.1.2 The Measurement System Frequency/Time Standard

The Type 3 Measurement System requires a stable frequency (5 or 10 MHz, for example) and/or time pulse (1 PPS) output to the receiver or a time interval counter. The frequency/time source must exhibit the following short-term stability requirements, at a minimum. An uninterruptable power supply is recommended for long-term observations.

Table 3-1. Measurement System Short-Term Stability Requirements

Averaging Interval	Time Domain Stability - $\sigma_y(\tau)$
1 second averaging:	1×10^{-9} s/s
10 second averaging:	1×10^{-10} s/s
100 second averaging:	1×10^{-11} s/s
1,000 second averaging:	1×10^{-12} s/s
10,000 second averaging:	1×10^{-12} s/s

3.1.3 The Measurement System GPS Receiver

The GPS receiver selected for use in a Measurement System must provide the following capabilities to support coverage and availability performance assessments:

- A communications interface compatible with the selected Measurement System processor and time/frequency standard.
- Output the PRN numbers of the satellites being tracked up to once per second.

All satellite-in-view tracking is desirable but not mandatory. The receiver antenna must be installed at a surveyed location for Type 2 or 3 Measurement Systems. The service standard assumes a survey accuracy of at least 1 meter (1σ) in each local coordinate axis. The GPS receiver must provide the following minimum capabilities to support position accuracy and service reliability performance assessments:

- Measurement data outputs up to once per second.
- Navigation message data output upon request or upon detection of an update.

The GPS receiver, working in concert with the Measurement System processor and frequency/time standard, must provide the following minimum capabilities to support time transfer accuracy performance assessments:

- Measurement timing must be based upon satellite ensemble time, an external reference or a selected satellite reception time tag -- regardless of the method used, measurement time tag precision with respect to reference time must be no worse than 10 ns RMS.
- Range or range residual measurement outputs up to once per second.

3.2 Minimum Position Error Measurement Processing Requirements

This section defines the specific process for computing instantaneous position solution error vectors. Many GPS receivers use sophisticated processing techniques such as range residual smoothing, velocity aiding, Kalman filters, all-in-view satellite solutions, etc. The minimum performance statistics are however based upon mapping instantaneous range residuals into a user position residual vector through the linearized position solution from a stationary, surveyed location. This process will result in the measurement of positioning and timing error characteristics which a receiver designed in accordance with the minimum requirements established in the Signal Specification can reasonably be expected to experience.

STEP 1. Select optimum four satellites based upon minimum PDOP. Update every five minutes, or whenever a satellite being used in the solution sets. See Step 6 for computation of the **K**-matrix terms. Note that the K terms used in the DOP computation may be computed using either the almanac or each satellite's ephemeris.

$$PDOP = \left[\sum_{i=1}^{3} \sum_{j=1}^{4} K_{ij}^2 \right]^{\frac{1}{2}}$$

STEP 2. Measure the pseudo range to each satellite. Each of the four measurements must have a reception timetag within ±0.5 seconds of the solution time. The reception timetag is based upon Measurement System time, and the transmission timetag is based upon satellite time.

$$PR_{measured}^{svi}\left(t_{received}\right) = c\left(t_{received}^{svi} - t_{transmitted}^{svi}\right)$$

Note that the pseudo range must be corrected based upon propagation path and timing error effect corrections defined in the SPS Signal Specification. c equals the speed-of-light in a vacuum (299,792,458 meters/second) as defined in the SPS Signal Specification, Section 2.5.1.

STEP 3. Read the ephemeris for each of the four satellites, in accordance with the SPS Signal Specification. Compute each satellite's ECEF position at the time of transmission. Apply the Earth rotation correction terms defined in the SPS Signal Specification to the site coordinates. Compute the predicted pseudo range for each satellite. (Readers should note that this predicted pseudo range computation yields what is alternatively identified as the *geometric range* in the SPS Signal Specification, Section 2.5.4.2).

$$PR_{predicted}^{svi} = \left\| \overline{R}_{predicted}^{svi}\left(t_{transmitted}\right) - \overline{R}_{site} \right\|$$

where: $\overline{R}_{predicted}^{svi}\left(t_{transmitted}\right)$ = Estimated position of i^{th} satellite at time of transmission

$\overline{R}_{site}$ = Location of receiver antenna, corrected for Earth rotation effects

STEP 4. Compute the range residual for each satellite. Given that $t_{received}$ is within ±0.5 seconds of the position solution time t_k, the range residual is associated with the k^{th} position solution time. NOTE: readers should not confuse the variable t_k as it is used in this Annex with its usage in the Signal Specification (Section 2.5.4, Table 2-15). t_k is used in the Signal Specification to define the difference between epoch time and current GPS time; it is used in this Annex to define an arbitrary k^{th} position solution time.

$$\Delta r_{svi}\left(t_k\right) = PR_{measured}^{svi}\left(t_{received}\right) - PR_{predicted}^{svi}\left(t_{received}\right)$$

STEP 5. Compute the position solution geometry matrix **G**, and rotate it into local coordinates. The **G**-matrix (defined below) is composed of four row vectors: one for each of the four satellites in the position solution. Each row vector contains the x, y, z and time coordinate direction cosines associated with one of the four satellite-to-user vector geometries, as they are defined in the WGS-84 ECEF coordinate system.

$$G_{xyz} = \begin{bmatrix} \frac{x_{sv1} - x_{site}}{R_{sv1} - ct_b} & \frac{y_{sv1} - y_{site}}{R_{sv1} - ct_b} & \frac{z_{sv1} - z_{site}}{R_{sv1} - ct_b} & 1 \\ \frac{x_{sv2} - x_{site}}{R_{sv2} - ct_b} & \frac{y_{sv2} - y_{site}}{R_{sv2} - ct_b} & \frac{z_{sv2} - z_{site}}{R_{sv2} - ct_b} & 1 \\ \frac{x_{sv3} - x_{site}}{R_{sv3} - ct_b} & \frac{y_{sv3} - y_{site}}{R_{sv3} - ct_b} & \frac{z_{sv3} - z_{site}}{R_{sv3} - ct_b} & 1 \\ \frac{x_{sv4} - x_{site}}{R_{sv4} - ct_b} & \frac{y_{sv4} - y_{site}}{R_{sv4} - ct_b} & \frac{z_{sv4} - z_{site}}{R_{sv4} - ct_b} & 1 \end{bmatrix} = \begin{bmatrix} G_x^{sv1} & G_y^{sv1} & G_z^{sv1} & 1 \\ G_x^{sv2} & G_y^{sv2} & G_z^{sv2} & 1 \\ G_x^{sv3} & G_y^{sv3} & G_z^{sv3} & 1 \\ G_x^{sv4} & G_y^{sv4} & G_z^{sv4} & 1 \end{bmatrix}$$

where:

$\{x_{site}, y_{site}, z_{site}\}$ = Station location in Cartesian coordinates

$\{x_{svi}, y_{svi}, z_{svi}\}$ = i^{th} satellite position coordinates at transmission time based upon navigation message contents

R_{svi} = Estimated range from user to i^{th} satellite -- can use predicted pseudo range.

ct_b = Bias between Measurement System time and GPS time, multiplied by the speed of light -- time should be managed such that the bias value is nominally zero.

Use the coordinate rotation matrix $\mathbf{S}$ to rotate each of the $\mathbf{G}$-matrix row vectors into local coordinates. The $\mathbf{S}$-matrix is defined below.

$$\mathbf{S} = \begin{bmatrix} -\sin\lambda_{site} & \cos\lambda_{site} & 0 & 0 \\ -\sin\phi_{site}\cos\lambda_{site} & -\sin\phi_{site}\sin\lambda_{site} & \cos\phi_{site} & 0 \\ \cos\phi_{site}\cos\lambda_{site} & \cos\phi_{site}\sin\lambda_{site} & \sin\phi_{site} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where: $\{\phi_{site}, \lambda_{site}\}$ = Station latitude and longitude in local coordinates

The $\mathbf{G}$-matrix row vector rotation is defined below. The result of the rotation is a new $\mathbf{G}$-matrix, defined with respect to local coordinate axes. Note that the time axis remains invariant through the rotation process.

$$\mathbf{G}_{enu} = \left[\mathbf{S} \times \begin{bmatrix} G_x^{sv1} \\ G_y^{sv1} \\ G_z^{sv1} \\ 1 \end{bmatrix} \vdots \; \mathbf{S} \times \begin{bmatrix} G_x^{sv2} \\ G_y^{sv2} \\ G_z^{sv2} \\ 1 \end{bmatrix} \vdots \; \mathbf{S} \times \begin{bmatrix} G_x^{sv3} \\ G_y^{sv3} \\ G_z^{sv3} \\ 1 \end{bmatrix} \vdots \; \mathbf{S} \times \begin{bmatrix} G_x^{sv4} \\ G_y^{sv4} \\ G_z^{sv4} \\ 1 \end{bmatrix} \right]$$

STEP 6. Compute the instantaneous position solution error for the $k^{\underline{th}}$ solution time.

$$\Delta\bar{\mathbf{x}}(t_k) = \mathbf{G}_{enu}^{-1}\Delta\bar{\mathbf{r}}(t_k) = \mathbf{K}\Delta\bar{\mathbf{r}}(t_k), \text{ or } \begin{bmatrix} \Delta e(t_k) \\ \Delta n(t_k) \\ \Delta u(t_k) \\ \Delta t(t_k) \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} \\ K_{21} & K_{22} & K_{23} & K_{24} \\ K_{31} & K_{32} & K_{33} & K_{34} \\ K_{41} & K_{42} & K_{43} & K_{44} \end{bmatrix} \begin{bmatrix} \Delta r_{sv1}(t_k) \\ \Delta r_{sv2}(t_k) \\ \Delta r_{sv3}(t_k) \\ \Delta r_{sv4}(t_k) \end{bmatrix}$$

where:

t_k = $k^{\underline{th}}$ solution time corresponding to the signal reception times for the four satellites

$\Delta\bar{\mathbf{x}}(t_k)$ = Position solution error vector in local coordinates (east, north, up and time) at the $k^{\underline{th}}$ solution time

$\Delta\bar{\mathbf{r}}(t_k)$ = $\Delta r_{svi}(t_k)$ values from Step 4, for the four satellites used in the $k^{\underline{th}}$ position solution

SECTION 4.0 Performance Measurement Algorithms

This section defines the measurement algorithms for evaluating GPS performance against the established performance standards. The standards which will be used to assess measurement results are defined prior to the definition of the associated algorithm. Each algorithm is stated in terms of the steps which must be followed to correctly implement the algorithm. Where necessary, specific equations are provided to support algorithm implementation.

Note that interpolation is not required between points to determine 95% or 99.99% confidence values. It is expected that less than 0.1% uncertainty will be induced in any confidence interval value, as long as sample size and rate requirements are met.

The following nomenclature is used in the measurement algorithm definitions.

- MDATA - Number of missed data points over the measurement interval (due to equipment failure, etc)
- MCOV - Number of points where coverage did not meet standard conditions
- MAVL - Number of points where service availability did not meet standard conditions
- MREL - Number of points where service reliability did not meet standard conditions

4.1 Coverage Measurement Algorithm

The standard to be used to evaluate coverage performance is defined below:

Coverage Standard	Conditions and Constraints
$C_{4SV} \geq 96.9\%$ 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 obscura • Standard is predicated on 24 operational satellites, as the constellation is defined in the almanac

The coverage performance algorithm is defined in the following steps.

STEP 1. Use the almanac from the current constellation to generate satellite position estimates (including unhealthy satellites) every second over 24 hours.

STEP 2. Generate elevation angles for each satellite with respect to the desired location.

STEP 3. If four or more satellites are visible (elevation angle above the mask angle of 5°) at the k^{th} time, select four satellites based upon the set which provides the smallest PDOP. If a set is found that provides a PDOP of six or less, the instantaneous coverage flag (C_p) is equal to one. If less than four satellites are visible or a PDOP of six or less is not supported by any combination of four satellites, C_p is equal to zero.

STEP 4. Compute the coverage percentage (C_{4SV}), based upon the instantaneous coverage values.

$$S_{COV} = 86{,}400$$

$$C_{4SV} = \frac{\sum_{p=1}^{S_{COV}} C_p}{S_{COV}} \times 100\%$$

4.2 Service Availability Measurement Algorithm

The standards to be used to evaluate service availability performance are defined below:

Service Availability Standard	Conditions and Constraints
$A_{AVE} \geq 99.16\%$ 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
$A_{4SV} \geq 83.92\%$ 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

The service availability performance algorithm is defined in the following steps.

STEP 1. Use receiver at desired location to track (nominally) all satellites in view.

STEP 2. Check coverage -- determine whether or not coverage standard conditions are satisfied each second over 24 hours. If coverage is not available at a time, service availability is not assessed at that time. The number of points not qualified to support a service availability assessment is defined by the quantity MCOV.

$$MCOV = 1 - \sum_{p=1}^{S_{COV}} C_p$$

STEP 3. For each time increment, use the ephemeris to determine whether or not all four satellites are set healthy. If so, then the service availability flag (A_p) equals one. If not, A_p equals zero. If one or more of the satellites providing coverage are unavailable, recompute the optimum selection of four based upon the remaining satellites. If a satellite combination providing a PDOP of six or less is not available, A_p equals zero.

STEP 4. Compute S_{AVL}, the total number of valid service availability measurement data points. MDATA equals the number of sample points where measurements were not taken, due to factors such as equipment failure. Compute the daily service availability percentage (A_{4SV}), based upon the instantaneous service availability values.

$$S_{AVL} = 86400 - MCOV - MDATA$$

$$A_{4SV}(day_d) = \frac{\sum_{p=1}^{S_{AVL}} A_p}{S_{AVL}} \times 100\%$$

STEP 5. Compute the average daily service availability percentage (A_{AVE}), based upon thirty contiguous days of daily service availability values. Each of the daily values (A_{4SVd}) are computed using the four steps defined above.

$$A_{AVE} = \frac{\sum_{d=1}^{30} A_{4SV}(day_d)}{30}$$

4.3 Service Reliability Measurement Algorithm

The standard to be used to evaluate service reliability performance is defined below:

Service Reliability Standard	Conditions and Constraints
$R_{AVE} \geq 99.79\%$ single point average	• Conditioned on coverage and service availability standards • 500 meter NTE predictable horizontal error reliability threshold • Standard based on a measurement interval of one year; average of daily values from the worst-case point on the globe • Standard predicated on a maximum of 18 hours of major service failure behavior over the measurement interval

Service reliability is evaluated in terms of the accumulated service failure duration, as defined below.

STEP 1. Use receiver at desired location to track (nominally) all satellites in view each second over a 24 hour period.

STEP 2. Check service availability -- determine whether or not service availability standard conditions are satisfied each second. If the service is not available at a time, service reliability is not assessed at that time. The number of points not qualified to support a service reliability assessment is defined by the quantity MAVL.

$$MAVL = 1 - \sum_{p=1}^{S_{AVL}} A_p$$

STEP 3. Measure the instantaneous predictable horizontal error, as defined in Section 4.4.1.1, Steps 1-3.

STEP 4. Determine whether the instantaneous horizontal error exceeds 500 meters. If so, the service reliability flag (R_p) equals one. If not, R_p equals zero.

STEP 5. Compute S_{REL}, the total number of valid service reliability measurement data points. MDATA equals the number of sample points where measurements were not taken, due to such factors as equipment failure. Compute the service reliability over 24 hours.

$$S_{REL} = 86400 - MCOV - MAVL - MDATA$$

$$R(day_d) = \frac{\sum_{p=1}^{S_{REL}} R_p}{S_{REL}}$$

STEP 6. Compute the average daily service reliability (R_{AVE}) over a year, based upon 365 days' worth of daily reliability values.

$$R_{AVE} = \frac{\sum_{d=1}^{365} R(day_d)}{365} \times 100\%$$

4.4 Accuracy Measurement Algorithms

The accuracy measurement algorithms are segregated into the four different aspects of accuracy: predictable, repeatable, relative and time transfer accuracy. The standards to be used to evaluate accuracy performance are defined prior to the algorithm for each respective aspect of accuracy.

Once accuracy data is collected over the 24 hour measurement interval, check service reliability and determine whether or not service reliability standard conditions are satisfied each second. If the service is not reliable at a time, accuracy is not assessed at that time. The number of points not qualified to support an accuracy assessment is defined by the quantity MREL. Compute S_{ACC}, the total number of valid accuracy measurement data points. MDATA equals the number of sample points where measurements were not taken, due to such factors as equipment failure.

$$MREL = 1 - \sum_{p=1}^{S_{REL}} R_p$$

$$S_{ACC} = 86400 - MCOV - MAVL - MREL - MDATA$$

4.4.1 Predictable Accuracy Measurement Algorithm

The standards to be used to evaluate predictable accuracy performance are defined below:

Predictable Accuracy Standard	Conditions and Constraints
$\Delta HPRE_{95} \leq 100$ meters horizontal error 95% of time $\Delta UPRE_{95} \leq 156$ meters vertical error 95% of time $\Delta HPRE_{99.99} \leq 300$ meters horizontal error 99.99% of time $\Delta UPRE_{99.99} \leq 500$ meters vertical error 99.99% of time	• Conditioned on coverage, service availability and service reliability standards • Standard based on a measurement interval of 24 hours, for any point on the globe

4.4.1.1 Horizontal Predictable Accuracy Measurement

The horizontal predictable accuracy performance algorithm is defined in the following steps.

STEP 1. Compute instantaneous position solutions every second for 24 hours.
STEP 2. Compute the east and north instantaneous errors (in meters) at each time t_k.

$$\Delta e(t_k) = [\lambda_{measured}(t_k) - \lambda_{site}]111319.4908 \cos\phi_{site}$$

$$\Delta n(t_k) = [\phi_{measured}(t_k) - \phi_{site}]111319.4908$$

or alternatively,

$$\Delta e(t_k) = K_{11}\Delta r_{sv1}(t_k) + K_{21}\Delta r_{sv2}(t_k) + K_{31}\Delta r_{sv3}(t_k) + K_{41}\Delta r_{sv4}(t_k)$$

$$\Delta n(t_k) = K_{12}\Delta r_{sv1}(t_k) + K_{22}\Delta r_{sv2}(t_k) + K_{32}\Delta r_{sv3}(t_k) + K_{42}\Delta r_{sv4}(t_k)$$

STEP 3. Compute the instantaneous horizontal error.

$$\Delta H(t_k) = \left[\left(\Delta e(t_k)\right)^2 + \left(\Delta n(t_k)\right)^2 \right]^{1/2}$$

STEP 4. Rank order the measurements, and find the n^{th} sample associated with the 95^{th} percentile. S_{ACC} equals the number of samples over the measurement interval.

$\Delta HPRE_{95}$ = ΔH value at n = INTEGER(0.95 x S_{ACC})

Use the same process (Steps 1-3) to find the n^{th} sample associated with the 99.99 percentile.

$\Delta HPRE_{99.99}$ = ΔH value at n = INTEGER(0.9999 x S_{ACC})

4.4.1.2 Vertical Predictable Accuracy Measurement

The vertical predictable accuracy performance algorithm is defined in the following steps.

STEP 1. Compute instantaneous position solutions every second for 24 hours.
STEP 2. Compute the instantaneous vertical error (in meters) at each time t_k.

$$\Delta u(t_k) = \text{Altitude}_{\text{measured}}(t_k) - \text{Altitude}_{\text{site}}$$

or alternatively,

$$\Delta u(t_k) = K_{13}\Delta r_{sv1}(t_k) + K_{23}\Delta r_{sv2}(t_k) + K_{33}\Delta r_{sv3}(t_k) + K_{43}\Delta r_{sv4}(t_k)$$

STEP 3. Take the absolute value of each measurement, rank order the measurements, and find the n^{th} sample associated with the 95^{th} percentile. S_{ACC} equals the number of samples over the measurement interval.

$\Delta UPRE_{95}$ = Δu value at n = INTEGER(0.95 x S_{ACC})

Use the same process (Steps 1-2) to find the n^{th} sample associated with the 99.99 percentile.

$\Delta UPRE_{99.99}$ = Δu value at n = INTEGER(0.9999 x S_{ACC})

4.4.2 Repeatable Accuracy Measurement Algorithm

The standards to be used to evaluate repeatable accuracy performance are defined below:

Repeatable Accuracy Standard	Conditions and Constraints
$\Delta HREP_{95} \leq$ 141 meters horizontal error 95% of time $\Delta UREP_{95} \leq$ 221 meters vertical error 95% of time	• Conditioned on coverage, service availability and service reliability standards • Standard based on a measurement interval of 24 hours, for any point on the globe

4.4.2.1 Horizontal Repeatable Accuracy Measurement

The horizontal repeatable accuracy performance algorithm is defined in the following steps.

STEP 1. Measure position at time t_k. Repeat each second for 24 hours plus Δt.
STEP 2. Measure position at time $t_k+\Delta t$. Δt must be longer than the position error correlation time constant. 15 minutes is recommended as the minimum size.
STEP 3. Compute the difference in position between the two times. If measurements are taken from a surveyed benchmark, use the error vectors taken at the two times.

$\Delta\overline{P}_{repeat}(t_k + \Delta t) = \Delta\overline{P}(t_k + \Delta t) - \Delta\overline{P}(t_k)$, where the east and north components are:

EAST: $\Delta e_{repeat}(t_k + \Delta t) = \Delta e(t_k + \Delta t) - \Delta e(t_k)$
NORTH: $\Delta n_{repeat}(t_k + \Delta t) = \Delta n(t_k + \Delta t) - \Delta n(t_k)$

If measurements are taken without a survey, directly compute the repeatable error vector and convert the east and north errors from an angular to a linear quantity.

$\Delta\overline{P}_{repeat}(t_k + \Delta t) = \overline{P}(t_k + \Delta t) - \overline{P}(t_k)$, where the east and north components are:

$\Delta\phi = \phi_{measured}(t_k + \Delta t) - \phi_{measured}(t_k)$; difference in latitude measurements
$\Delta\lambda = \lambda_{measured}(t_k + \Delta t) - \lambda_{measured}(t_k)$; difference in longitude measurements

EAST: $\Delta e_{repeat}(t_k + \Delta t) = [\Delta\lambda]111319.4908\cos\left[\phi_{measured}(t_k + \Delta t) - \frac{\Delta\phi}{2}\right]$

NORTH: $\Delta n_{repeat}(t_k + \Delta t) = \Delta\phi * 111319.4908$

STEP 4. Compute the difference in horizontal position magnitude at $t_k+\Delta t$.

$$\Delta H_{repeat}(t_k + \Delta t) = \left[\left(\Delta e_{repeat}(t_k + \Delta t)\right)^2 + \left(\Delta n_{repeat}(t_k + \Delta t)\right)^2\right]^{\frac{1}{2}}$$

STEP 5. Rank order the measurements, and find the n^{th} sample associated with the 95^{th} percentile. S_{ACC} equals the number of samples over the measurement interval.

$\Delta HREP_{95} = \Delta H_{repeat}$ value at n = INTEGER(0.95 x S_{ACC})

4.4.2.2 Vertical Repeatable Error Measurement

The vertical repeatable accuracy performance algorithm is defined in the following steps.

STEP 1. Repeat steps 1 and 2 from the horizontal repeatable position error computation (Section 4.4.2.1).
STEP 2. Compute the difference in altitude between the two times.

$\Delta u_{repeat}(t_k + \Delta t) = \Delta u(t_k + \Delta t) - \Delta u(t_k)$

STEP 3. Take the absolute value of each measurement, rank order the measurements, and find the n^{th} sample associated with the 95^{th} percentile. S_{ACC} equals the number of samples over the measurement interval.

$\Delta UREP_{95} = \Delta u_{repeat}$ value at n = INTEGER(0.95 x S_{ACC})

4.4.3 Relative Accuracy Measurement Algorithm

The standards to be used to evaluate relative accuracy performance are defined below:

Relative Accuracy Standard	Conditions and Constraints
$\Delta HREL_{95} \leq 1.0$ meters horizontal error 95% of time $\Delta UREL_{95} \leq 1.5$ meters vertical error 95% of time	• Conditioned on coverage, service availability and service reliability standards • Standard based on a measurement interval of 24 hours, for any point on the globe • Standard presumes that the receivers base their position solutions on the same satellites, with position solutions computed at approximately the same time

Note that the relative accuracy standards are based upon signal-in-space errors, and do not include the receiver ranging measurement contribution to positioning error. Users who measure relative accuracy can expect to experience 6 meters horizontal error (95%) and 9 meters vertical error (95%), due to the contribution of the two receivers to the relative position solution error.

4.4.3.1 Horizontal Relative Accuracy Measurement

The horizontal relative accuracy performance algorithm is defined in the following steps.

STEP 1. Take ranging measurements and navigation message data from two receivers for all satellites in view each second for 24 hours. The receivers must be colocated or sitting at surveyed locations (recommended to be within 40 kilometers of one another, to support consistent satellite tracking coordination between the two receivers).

STEP 2. Use the ranging measurements and navigation data to generate range residuals for both sets of measurements.

STEP 3. Use the range residuals to generate (in post-processing) position residual estimates for each measurement set. The satellite selection strategy must coordinate satellite selections between the two receivers. The position solutions from both receivers must meet coverage, service availability and service reliability conditions.

STEP 4. Compute the instantaneous predictable error for the two receivers. Rotate the resulting ECEF vectors into the local coordinates of either of the two receivers. Compute the relative horizontal error components.

$$\Delta e_{rel}(t_k) = \Delta e_{receiver1}(t_k) - \Delta e_{receiver2}(t_k)$$
$$\Delta n_{rel}(t_k) = \Delta n_{receiver1}(t_k) - \Delta n_{receiver2}(t_k)$$

$$\Delta H_{rel}(t_k) = \left[\left(\Delta e_{rel}(t_k)\right)^2 + \left(\Delta n_{rel}(t_k)\right)^2\right]^{1/2}$$

STEP 5. Rank order the measurements, and find the n^{th} sample associated with the 95^{th} percentile. S_{ACC} equals the number of samples over the measurement interval.

$$\Delta HREL_{95} = \Delta H_{rel} \text{ value at } n = \text{INTEGER}(0.95 \times S_{ACC})$$

4.4.3.2 Vertical Relative Accuracy Measurement

The vertical relative accuracy performance algorithm is defined in the following steps.

STEP 1. Perform Steps 1-3 in the horizontal relative accuracy methodology (Section 4.3.3.1).

STEP 2. Compute the instantaneous relative vector between the two receivers. Rotate the resulting ECEF vector into the local coordinates of either of the two receivers.

$$\Delta u_{rel}(t_k) = \Delta u_{receiver1}(t_k) - \Delta u_{receiver2}(t_k)$$

STEP 3. Take the absolute value of each measurement, rank order the measurements, and find the n^{th} sample associated with the 95^{th} percentile. S_{ACC} equals the number of samples over the measurement interval.

$$\Delta UREL_{95} = \Delta u_{rel} \text{ value at } n = \text{INTEGER}(0.95 \times S_{ACC})$$

4.4.3.3 A Note on Relative Accuracy with Uncoordinated Satellite Tracking

Note that in the event that measurements are taken with no attempt to coordinate satellite tracking, accuracy will vary widely as a function of distance between receivers and the number of satellites which their solutions have in common. Accuracy can be as good as that provided by the correlated solution, and as bad as repeatable error over long sample intervals from completely uncorrelated solutions. Receivers relatively close together will tend to select common satellites the majority of the time, so accuracy should tend towards the completely correlated values.

4.4.4 Time Transfer Accuracy Measurement Algorithm

The standard to be used to evaluate time transfer accuracy performance is defined below:

Time Transfer Accuracy Standard	Conditions and Constraints
$\Delta t_{u95} \leq 340$ nanoseconds time transfer error 95% of time	• Conditioned on coverage, service availability and service reliability standards • Standard based upon SPS receiver time as computed using the output of the position solution • Standard based on a sample interval of 24 hours, for any point on the globe • Standard is defined with respect to Universal Coordinated Time, as it is maintained by the United States Naval Observatory

The time transfer accuracy performance algorithm is defined in the following steps.

STEP 1. Measure instantaneous range residuals for the satellites selected for the optimum position solution. Range residual time tags must be based upon a measurement system timing system tied to USNO UTC to within 10 ns Root Mean Square (RMS). Use the residuals in the linearized navigation equations to generate a solution each minute over 24 hours. The position solution must meet coverage, service availability and service reliability conditions.

STEP 2. From the position solution equations, estimate the receiver's time offset with respect to GPS time.

$$\Delta t_u(t_k) = \sum_{i=1}^{4} K_{4i} \frac{\Delta r_{svi}(t_k)}{c}, \text{ where c = WGS-84 value for speed-of-light in a vacuum}$$

STEP 3. Apply the UTC correction from the navigation message to the GPS time offset estimate.

STEP 4. Take the absolute value of each measurement, rank order the measurements, and find the n^{th} sample associated with the 95^{th} percentile. S_{ACC} equals the number of samples over the measurement interval.

$$\Delta t_{u95} = \Delta t_u \text{ value at } n = \text{INTEGER}(0.95 \times S_{ACC})$$