GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE PERFORMANCE STANDARD

OCTOBER, 2001
ASSISTANT SECRETARY OF DEFENSE
FOR
COMMAND, CONTROL, COMMUNICATIONS, AND INTELLIGENCE

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ASSISTANT SECRETARY OF DEFENSE
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COMMAND, CONTROL,
COMMUNICATIONS, AND
INTELLIGENCE

October 4, 2001

FOREWORD

This document defines the levels of performance the U.S. Government makes available to civil users through the GPS Standard Positioning Service (SPS). It has been approved by the DoD PosNav Executive committee. Please refer any questions or comments, in writing, to the following:

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TABLE OF CONTENTS

Figures and Tables

SECTION 1 The GPS Standard Positioning Service

The Global Positioning System (GPS) is a space-based radionavigation system managed and operated by the United States (U.S.) Government. GPS was designed as a dual-use system with the primary purpose of enhancing the effectiveness of U.S. and allied military forces. GPS provides a substantial military advantage and is now being integrated into virtually every facet of military operations. GPS is also becoming an integral component of the Global Information Infrastructure, with applications ranging from mapping and surveying to international air traffic management and global climate change research. 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 and other authorized users of the United States and its allies equipped with PPS receivers. The Standard Positioning Service (SPS) was originally designed to provide civil users with a less accurate positioning capability than PPS through the use of a technique known as Selective Availability (SA). On May 1, 2000, the President directed the U.S. Department of Defense (DoD) to discontinue the use of SA effective midnight May 1, 2000. This edition of the SPS Performance Standard establishes new performance standards that reflect the removal of SA.

1.1 Purpose

The SPS Performance Standard defines levels of performance the U.S. Government commits to provide to civil GPS users. This document is written to satisfy the following objectives:

1) Identify performance standards the U.S. Government uses to manage SPS performance.
2) Standardize SPS performance parameter definitions and assessment methodologies.
3) Describe historical SPS performance characteristics and ranges of behavior.

Appendix A to this document provides information to the civil community concerning historical performance, ranges of performance possible under varying operational conditions, and operational characteristics of the GPS constellation. Appendix A is provided for informational purposes only.

Appendix B to this document provides a list of key terms and definitions, and acronyms used in the SPS Performance Standard.

1.2 Scope

The SPS Performance Standard is published by the Office of the Secretary of Defense, in accordance with the Memorandum of Agreement (MOA) between the DoD and the Department of Transportation (DOT) regarding civil use of the Global Positioning System (Section 5, Paragraph a).

In keeping with the purpose defined in the DoD/DOT MOA, this document defines standards for SPS Signal-in-Space (SIS) performance. SPS performance standards are independent of how the user applies the basic positioning and timing services provided. These performance standards are based on signal-in-space performance. Contributions of ionosphere, troposphere, receiver, multipath, or interference are not included.

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

1.3 The GPS Standard Positioning Service

The GPS SPS is a positioning and timing service provided on the GPS L1 signal. The L1 signal, transmitted by all GPS satellites, contains a Coarse/Acquisition (C/A) code and a navigation data message. The GPS L1 signal also contains a Precision P(Y) code that is reserved for military use and is not a part of the SPS.

The L-band SPS ranging signal is a 2.046 MHz null-to-null bandwidth signal centered about L1. The transmitted ranging signal that comprises the GPS-SPS is not limited to the null-to-null signal and extends through the band 1563.42 to 1587.42 MHz.

GPS satellites also transmit a second ranging signal known as L2. The L2 signal is not part of the SPS. Therefore, SPS performance standards are not predicated upon use of L2, or use of L1/L2 carrier tracking for other than code acquisition and tracking purposes. Until such time as a second coded civil GPS signal is operational, the U.S. Government has agreed to not intentionally reduce the current received minimum Radio Frequency signal strength of the P(Y)-coded signal on the L2 link, as specified in ICD-GPS-200C or to intentionally alter the P(Y)-coded signal on the L2 link. This does not preclude addition of codes or modifications to the L2 signal which do not change, or make unusable, the L2 P(Y)-coded signal as currently specified.

1.4 Global Positioning System Overview

Sufficient information is provided below to promote a common understanding of the nominal GPS baseline configuration. The GPS baseline system is comprised of three segments, whose purpose is to provide a reliable and continuous positioning and timing service to the GPS user community. These three segments are known as the Space Segment, Control Segment, and User Segment. The User Segment is comprised of receivers from a wide variety of U.S. and international agencies, in addition to the growing private user base.

1.4.1 The GPS Space Segment

The GPS space segment consists nominally of a constellation of 24 operational Block II satellites (Block II, IIA, and IIR).

Each satellite broadcasts 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 Performance Standard 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 Block IIA satellite's SPS ranging signal generation process is provided in Figure 1-1. The GPS satellite also transmits a second ranging signal known as L2, that supports PPS user two-frequency corrections. L2, like L1, is a spread spectrum signal and is transmitted at 1227.6 MHz.

The Block II satellites are designed to provide reliable service over a 7.5- to 10-year design life, depending on the production version, through a combination of space qualified parts, multiple redundancies for critical subsystems, and internal diagnostic logic. The Block II satellite 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, although Block II/IIA satellites may experience a 6- to 24-second disruption upon transition to the new upload.

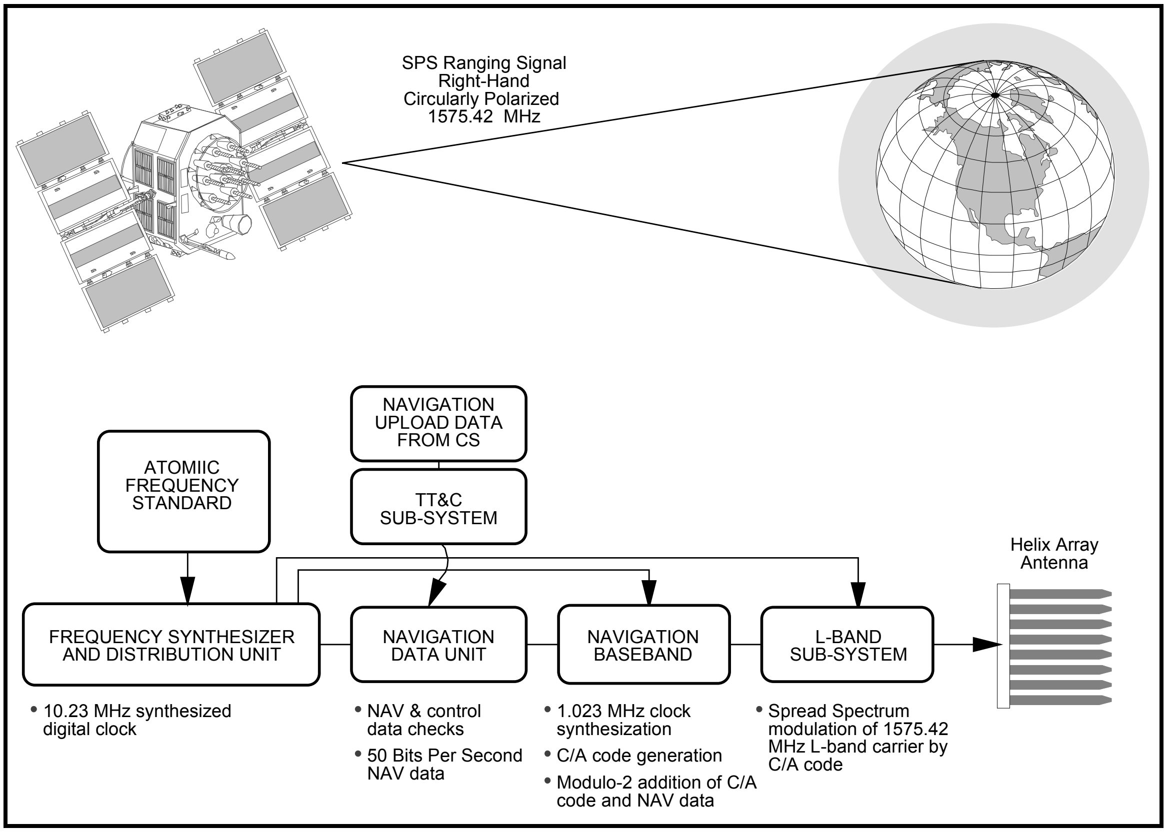

Figure 1-1. Block IIA SPS Ranging Signal Generation and Transmission

1.4.2 The GPS Control Segment

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

The MCS is located at Schriever 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.
- Managing 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.

In the event of a prolonged MCS outage, GPS operations can be moved to a contractor-owned BMCS located at Gaithersburg, MD. When required, personnel from the MCS deploy to the BMCS within 24 hours. The BMCS is operationally exercised approximately four times per year to ensure system capability.

The CS's four ground antennas provide a near real-time Telemetry, Tracking, and Commanding (TT&C) interface between the GPS satellites and the MCS. The six monitor stations provide near real-time satellite ranging measurement data to the MCS and support near-continuous monitoring of constellation performance. The current CS monitor stations provide approximately 93% global coverage, with all monitor stations operational, with a 5° elevation mask angle. The actual elevation angle that a monitor station acquires any given satellite varies due to several external factors.

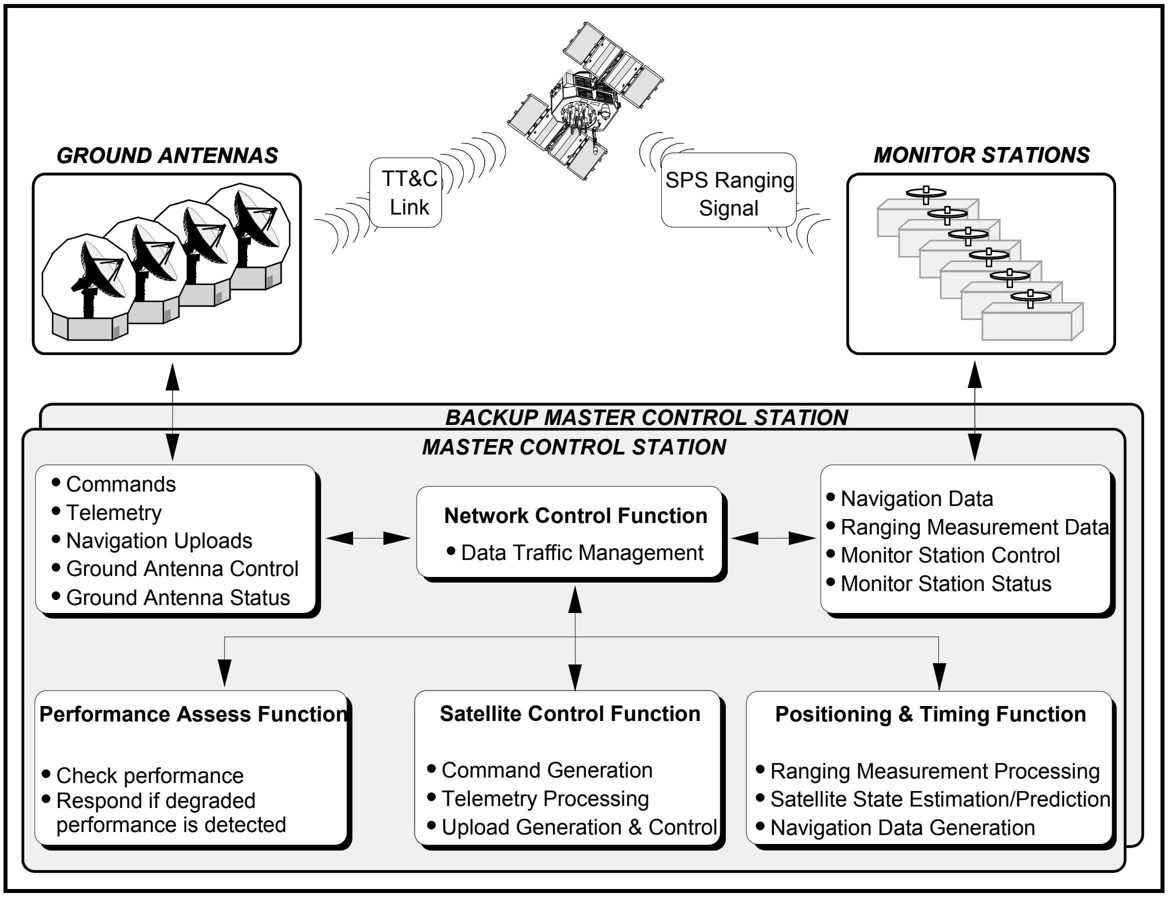

Figure 1-2. The GPS Control Segment

1.5 Current SPS Performance Assessment Concept and Limitations

The U.S. Government does not currently monitor and assess SPS performance in real time. The U.S. Government does monitor PPS SIS UREs for all satellites in view of Operational Control System (OCS) monitor stations in near-real time, to ensure they are meeting performance objectives. This monitoring is obviously constrained by holes in the current monitor station visibility patterns, and by monitor station and communications maintenance requirements. The U.S. Government intends to assess ways for improving its GPS monitoring and measurement capabilities in accordance with program plans, subject to resource limitations.

Performance summaries based on estimates of SPS SIS UREs are periodically generated, to provide feedback concerning GPS support for the SPS SIS URE performance standard. Additionally, the U.S. Government periodically assesses global constellation geometry behavior, and performs projections to anticipate potential Dilution of Precision (DOP) problems anywhere in the world. The U.S. Government uses monitor station measurements, constellation geometry and estimates of SPS SIS UREs to evaluate on a regular basis the ability of GPS to support SPS position accuracy and availability standards. However, these assessments may be several days after the fact.

GPS satellites automatically remove themselves from service when they experience any of a number of specified failure modes. When a service failure occurs that is not covered by the automatic removal capability, the U.S. Government will respond to the failure by removing the satellite from service in a prompt manner, subject to current monitor station and ground antenna visibility and reliability constraints. In order to detect satellite component failures unique to C/A code, the OCS monitor stations are configured to perform C/A to P(Y) code handover for each satellite track session when the satellite comes into view. However, this does not provide continuous, real-time monitoring of C/A performance.

Due to the reasons stated above, the risks inherent in implementing planned major modifications to the control segment and satellite block changes, as well as considerations for ensuring safety-of-life, there is a substantial margin introduced between the committed standards in Section 3 and the performance observed in Appendix A.

The U.S. Government does not directly monitor range rate or range acceleration error. URE rate-of-change is used internally by the OCS to estimate when a satellite may exceed service reliability limits, but the parameter is not tracked or reported within the OCS.

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SECTION 2 SPS Ranging Signal Characteristics and Minimum Usage Assumptions

This section provides an overview of the SPS ranging signal characteristics and the assumptions made to arrive at the performance standards. The representative receiver characteristics are used to provide a framework for defining SPS performance standards. They are not intended to impose any minimum requirements on receiver manufacturers or integrators. Receiver characteristics used in this standard are required to establish a frame of reference within which the SPS signal performance characteristics can be described.

The SPS Performance Standard is the authoritative U.S. document that defines the level of performance that the U.S. Government commits to provide to all civil users. Details on the technical characteristics of the SPS L-band carrier and the C/A code are defined in ICD-GPS-200C (current edition). The U.S. Government has established ICD-GPS-200C as the technical definition of interface requirements between the GPS constellation and SPS receivers. ICD-GPS-200C is the definitive document in matters concerning technical definition of GPS navigation signal characteristics and navigation message processing protocols.

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 Radio Frequency (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. This power level is defined for a representative SPS receiver located near the ground and tracking with a 3 dBi linearly polarized antenna above a 5° mask angle.

L1 is Bipolar-Phase Shift Key (BPSK) modulated with a Pseudo Random Noise (PRN) 1.023 MHz code known as the 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.

2.1.2 An Overview of the GPS Navigation Message

Each GPS satellite broadcasts 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 include information required to determine the following:

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

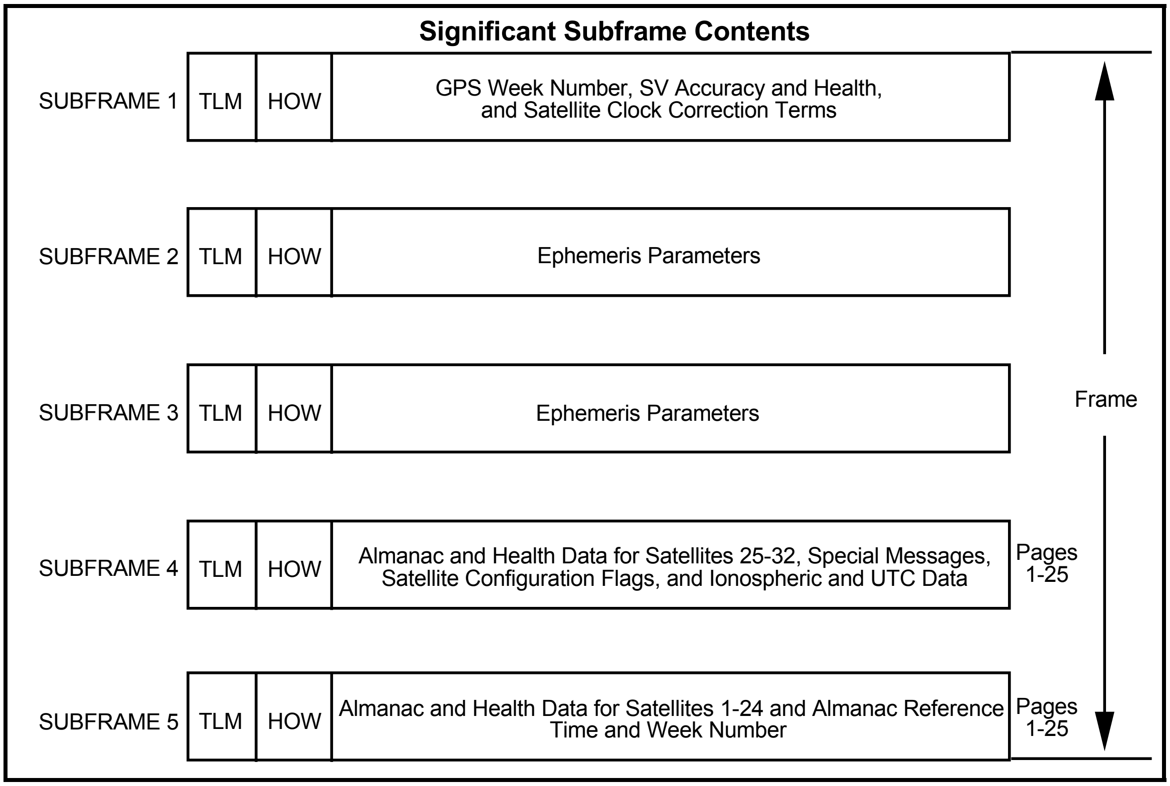

Figure 2-1. Navigation Message Content and Format Overview

2.2 Usage Assumptions for SPS Performance Standards

Operational SPS performance standards do not take into consideration any error source that is not under direct control of GPS constellation operations, such as:

- Ionosphere single-frequency model error
- Troposphere model error
- Signal reception interference, to include scintillation
- Receiver thermal noise
- Multipath

Since not all SPS receiver designs are within the purview of the U.S. Government, this document makes certain minimum assumptions concerning receiver characteristics and usage. These assumptions establish a frame of reference for deriving SPS operational performance standards.

Two generic types of SPS users are discussed in this section: navigation users and time transfer users. Whenever a receiver is discussed without mentioning one type of user or the other, the statement applies to representative receivers for both types of users.

This document assumes the use of a representative SPS receiver that:

- is designed in accordance with ICD-GPS-200C.
- is tracking all satellites in view above a 5° mask angle with respect to the local horizon (no local obscura are considered). It is assumed the receiver is operating in a nominal noise environment that does not interrupt receiver acquisition and tracking capabilities.

- accomplishes satellite position and geometric range computations in the most current realization of the World Geodetic System 1984 (WGS 84) Earth-Centered, Earth-Fixed (ECEF) coordinate system.
- generates a position and time solution from data broadcast by all satellites in view.
- compensates for dynamic Doppler shift effects on nominal SPS ranging signal carrier phase and C/A code measurements.
- reads the health field and status bits in the navigation message and excludes unhealthy satellites from the position solution.
- ensures the use of up-to-date and internally consistent ephemeris and clock data for all satellites it is using in its position solution.
- loses track in the event a GPS satellite stops transmitting C/A code.
- is operating at a surveyed location (for a time transfer receiver).

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SECTION 3 GPS SPS Performance Standards

This section establishes SPS performance standards for GPS operations. The U.S. Government is committed to operating GPS in accordance with these standards, in a manner consistent with system capabilities and subject to budgetary constraints. The U.S. Government reserves the right to adjust GPS constellation management practices as necessary to support military and civil end users. One of the potential adjustments includes a redefinition of the baseline constellation slots, as they are represented in Table 3-1. In the event of such a redefinition, the U.S. Government will provide an updated definition to the user community.

SPS performance standards are based on signal-in-space performance. Contributions of ionosphere, troposphere, receiver, multipath, or interference are not included. Position and time transfer performance estimates for a single-frequency user equipped with a representative receiver, inclusive of ionosphere, troposphere and receiver noise contributions, are provided in Appendix A, Section A-5.5.

SPS performance standards are established in a manner consistent with the following definitions:

- **Service Volume:** The spatial volume supported by SPS performance standards. Specifically, the SPS Performance Standard supports the terrestrial service volume. The terrestrial service volume covers from the surface of the Earth up to an altitude of 3,000 kilometers.
- **Availability of Position Dilution of Precision (PDOP):** The percentage of time over a specified time interval that the Position Dilution of Precision (PDOP) is less than or equal to a specified value.
- **SPS SIS User Range Error (URE) Statistic:**
  - ⇨ A satellite SPS SIS URE statistic is defined to be the Root Mean Square (RMS) difference between SPS ranging signal measurements (neglecting user clock bias and errors due to propagation environment and receiver), and "true" ranges between the satellite and an SPS user at any point within the service volume over a specified time interval.
  - ⇨ A constellation SPS SIS URE statistic is defined to be the average of all satellite SPS SIS URE statistics over a specified time interval.
- **Service Reliability:** The percentage of time over a specified time interval that the instantaneous SIS SPS URE is maintained within a specified reliability threshold at any given point within the service volume, for all healthy GPS satellites. The likelihood of the reliability threshold being broken is referred to as the Probability of Hazardously Misleading Information (HMI).
- **Service Availability:** The percentage of time over a specified time interval that the predicted position accuracy is less than a specified value for any point within the service volume.
- **Positioning Accuracy:** The statistical difference between position measurements and a surveyed benchmark for any point within the service volume over a specified time interval.
- **Time Transfer Accuracy Relative to UTC (USNO):** The difference at a specified probability between user UTC time estimates and UTC (USNO) at any point within the service volume over a specified time interval.

3.1 Constellation Management Standard

The current architecture for the constellation identifies nominal orbit slots for a 24-satellite constellation and tolerances for establishing and maintaining satellites within the slots. The baseline design for the GPS constellation is presented in Table 3-1. Slot assignments for the nominal constellation plan are specified in terms of the Right Ascension of the Ascending Node (RAAN) and the Argument of Latitude for a defined epoch.

Table 3-1. Reference Orbit Slot Assignments as of the Defined Epoch

SLOT	RAAN	Argument of Latitude	SLOT	RAAN	Argument of Latitude
A1	272.847°	268.126°	**D1**	92.847°	135.226°
A2	272.847°	161.786°	**D2**	92.847°	265.446°
A3	272.847°	11.676°	**D3**	92.847°	35.156°
A4	272.847°	41.806°	**D4**	92.847°	167.356°
B1	332.847°	80.956°	**E1**	152.847°	197.046°
B2	332.847°	173.336°	**E2**	152.847°	302.596°
B3	332.847°	309.976°	**E3**	152.847°	66.066°
B4	332.847°	204.376°	**E4**	152.847°	333.686°
C1	32.847°	111.876°	**F1**	212.847°	238.886°
C2	32.847°	11.796°	**F2**	212.847°	345.226°
C3	32.847°	339.666°	**F3**	212.847°	105.206°
C4	32.847°	241.556°	**F4**	212.847°	135.346°

EPOCH: 0000Z, 1 July 1993
GREENWICH HOUR ANGLE: $18^h\ 36^m\ 14.4^s$
REFERENCED TO FK5/J2000.00 COORDINATES

The rest of the reference orbit values are presented below:

- Groundtrack Equatorial Crossing: ± 2°
- Eccentricity: 0.00 – 0.02
- Inclination: 55° ± 3°
- Semi-major Axis: 26,559.7 kilometers ± 50 kilometers for Block IIR, ± 17 kilometers for Block II/IIA
- Longitude of the Ascending Node: ± 2°
- Argument of Perigee: ± 180°

Note that actual constellation RAAN values will change over each satellite's lifetime due to perturbation forces and variations in each unique orbit's nodal regression rate. It is also possible for inclination to drift out of the nominal tolerance. Maintenance of the Groundtrack Equatorial Crossing (GEC) and relative spacing of the constellation are therefore the controls employed to compensate for constellation drift and sustain constellation geometry at acceptable levels. The semi-major axis and orbital period shall be periodically adjusted to maintain the relative spacing of the satellite GECs to within ±2° of the chosen values. GEC values are chosen such that the position solution geometry criterion is continuously sustained for the core 24-satellite constellation.

3.2 Service Availability Standard

The U.S. Government commits to maintaining the Position Dilution of Precision (PDOP) in accordance with the following tolerances.

Table 3-2. Position Dilution of Precision Availability Standard

PDOP Availability Standard	Conditions and Constraints
≥ 98% global Position Dilution of Precision (PDOP) of 6 or less ≥ 88% worst site PDOP of 6 or less	• Defined for position solution meeting the representative user conditions and operating within the service volume over any 24-hour interval. • Based on using only satellites transmitting standard code and indicating "healthy" in the broadcast navigation message (sub-frame 1).

In support of the service availability standard, 24 operational satellites must be available on orbit with 0.95 probability (averaged over any day). At least 21 satellites in the 24 nominal plane/slot positions must be set healthy and transmitting a navigation signal with 0.98 probability (yearly averaged).

The U.S. Government's commitments for maintaining PDOP (Table 3-2) and constellation SPS SIS URE (see Section 3.3) result in support for a service availability standard as presented in Table 3-3.

Table 3-3. SPS Service Availability Standard

Service Availability Standard	Conditions and Constraints
≥ 99% Horizontal Service Availability average location ≥ 99% Vertical Service Availability average location	• 36 meter horizontal (SIS only) 95% threshold. • 77 meter vertical (SIS only) 95% threshold. • Defined for position solution meeting the representative user conditions and operating within the service volume over any 24-hour interval. • Based on using only satellites transmitting standard code and indicating "healthy" in the broadcast navigation message (subframe 1).
≥ 90% Horizontal Service Availability worst-case location ≥ 90% Vertical Service Availability worst-case location	• 36 meter horizontal (SIS only) 95% threshold. • 77 meter vertical (SIS only) 95% threshold. • Defined for position solution meeting the representative user conditions and operating within the service volume over any 24-hour interval. • Based on using only satellites transmitting standard code and indicating "healthy" in the broadcast navigation message (subframe 1).

3.3 Service Reliability Standard

The U.S Government commits to providing SPS service reliability in accordance with the following tolerances.

Table 3-4. Service Reliability Standard

Service Reliability Standard	Conditions and Constraints
≥ 99.94% global average	• 30-meter Not-to-Exceed (NTE) SPS SIS URE. • Standard based on a measurement interval of one year; average of daily values within the service volume. • Standard based on 3 service failures per year, lasting no more than 6 hours each.
≥ 99.79% worst case single point average	• 30-meter NTE SPS SIS URE. • Standard based on a measurement interval of one year; average of daily values from the worst-case point within the service volume. • Standard based on 3 service failures per year, lasting no more than 6 hours each.

The probability of Hazardously Misleading Information (HMI) shall be less than 0.002. A HMI event occurs when the SIS URE is greater than 30 meters while the satellite is set healthy but the User Range Accuracy (URA) multiplied out to 4.42 standard deviations is less than 30 meters.

3.4 Accuracy Standard

The U.S. Government commits to providing SPS SIS User Range Errors (UREs) in accordance with the tolerance established in Table 3-5. As indicated in Section 1.5, the U.S. Government does not directly monitor or verify SPS URE performance, but rather meets this standard through the monitoring of PPS UREs.

Table 3-5. Constellation SPS SIS URE Standard

SPS SIS URE Standard	Conditions and Constraints
≤ 6 meters RMS SIS SPS URE across the entire constellation	• Average of the constellation's individual satellite SPS SIS RMS URE values over any 24-hour interval, for any point within the service volume

The U.S. Government does not intend to impose range rate or range acceleration errors on the SPS signal.

The U.S. Government's commitments for maintaining PDOP (Table 3-2) and constellation SPS SIS URE (Table 3-5) result in support for position and time transfer accuracy standards as presented in Table 3-6. These accuracy standards were established based on the worst two of 24 satellites being removed from the constellation and a 6-meter constellation RMS SIS URE.

Table 3-6. Positioning and Timing Accuracy Standard

Accuracy Standard	Conditions and Constraints
Global Average Positioning Domain Accuracy • ≤ 13 meters 95% All-in-View Horizontal Error (SIS Only) • ≤ 22 meters 95% All-in-View Vertical Error (SIS Only)	• Defined for position solution meeting the representative user conditions • Standard based on a measurement interval of 24 hours averaged over all points within the service volume
Worst Site Positioning Domain Accuracy • ≤ 36 meters 95% All-in-View Horizontal Error (SIS Only) • ≤ 77 meters 95% All-in-View Vertical Error (SIS Only)	• Defined for position solution meeting the representative user conditions • Standard based on a measurement interval of 24 hours for any point within the service volume
Time Transfer Accuracy • ≤ 40 nanoseconds time transfer error 95% of time (SIS Only)	• Defined for time transfer solution meeting the representative user conditions • Standard based on a measurement interval of 24 hours averaged over all points within the service volume

3.5 GPS Status and Problem Reporting Standard

The U.S. Government provides notification of changes in constellation operational status that affect the service being provided to GPS users, or if the U.S. Government anticipates a problem in supporting performance standards established in this document. The current mechanism for accomplishing this notification is through the *Notice: Advisory to Navigation Users (NANU)*. NANUs are a primary input in the generation of GPS-related Notice to Airmen (NOTAM) and U.S. Coast Guard Local Notice to Mariners (LNM). Most outages affect both PPS and SPS users. However, since the GPS Control Segment currently monitors PPS, not SPS, in near real-time, notification of SPS unique service disruptions may be delayed. Since NANUs are currently tailored to PPS outages, notification of SPS unique outages may require the use of the general "free text" NANU vice a tailored template.

In the case of a scheduled event affecting service provided to GPS users, the U.S. Government will issue an appropriate NANU at least 48 hours prior to the event. In the case of an unscheduled outage or problem, notification will be provided as soon as possible after the event.

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APPENDIX A

GPS Documented Performance Characteristics

SECTION A-1 Introduction

GPS performance behavior is dynamic, given the use of satellites as “mobile beacons”. GPS performance may however be defined in a straightforward fashion with bounds placed upon the range of performance a user will experience. These bounds are established in the SPS Performance Standard, Section 3, as SPS operational performance standards. This Appendix provides a context in which to view GPS performance standards, through a definition of historical behavior and expected variations for each aspect of system performance.

A-1.1 Purpose

This Appendix describes documented GPS SPS performance as a function of time to aid the user in comparing historical delivered service to the service levels established in the SPS Performance Standard, Section 3. Although GPS performance has substantially exceeded established service levels, users should place full reliance on the standards of Section 3. This Appendix is to be used for information only.

A-1.2 Scope

The contents of this Appendix are provided for information purposes only, and do not constitute any commitment on the part of the U.S. Government. Historical performance does not guarantee future behavior. The U.S. Government retains the right to modify constellation management practices as necessary to meet or exceed performance standards.

A-1.3 An Overview of SPS Performance Parameters

This section provides a description of the basis for defining GPS performance parameters and their associated standards. Background is provided to promote an understanding of the underlying behavior described in succeeding sections.

A-1.3.1 Basis for Establishing SPS Performance Standards

The performance a GPS user experiences will vary widely due to many factors. With the removal of Selective Availability (SA), these variations have become much more pronounced. The primary factors that drive the performance a GPS user will experience are:

- Satellite availability.
- Signal-in-Space (SIS) User Range Errors (UREs) for satellites used in the solution, to include single-frequency and C/A code-unique code phase errors.
- Constellation geometry.
- Receiver design-dependent mask angle (nominal mask angle value, use of a fixed value versus dynamic selection).
- Type of solution (for positioning users – a four-satellite solution, a variant of over-determined solution to include all satellites-in-view, or a solution based on a variant of Receiver Autonomous Integrity Monitoring (RAIM)).

- Accuracy of United States Naval Observatory (USNO) GPS time offset predictions relative to Coordinated Universal Time (UTC (USNO)), for time transfer users.
- The signal propagation environment, to include ionosphere and troposphere delay effects, and scintillation.
- The signal reception environment, to include local terrain, multipath, local interference source effects and user platform dynamics.
- Receiver signal processing characteristics, thermal noise behavior, and quality of propagation environment delay effect models.

With so many factors driving the performance a user experiences, it is obvious that a single set of performance standards cannot hope to represent the service to be expected by all users. This situation is complicated even further by the fact that many factors affecting user performance are outside the control of the U.S. Government.

The U.S. Government's strategy for establishing coherent operational performance standards in the face of such complexity is as follows:

1) Formalize operational tolerances for core performance control parameters based on original GPS design criteria, current performance characteristics, and Operational Control System (OCS) operations tempo considerations.
2) Define system-level performance metrics that map the core performance control parameters through representative user assumptions into the position and time domain.
3) Define system-level operational performance standards that include only those factors that the U.S. Government controls.
4) Establish performance feedback mechanisms based on the system-level metrics to assure that operations in accordance with core performance control parameters, in fact, continue to support the performance standards.
5) Document nominal tolerances and management philosophies for core performance parameters to allow users to derive for themselves what their expectations should be for their unique application.

A-1.3.2 A Brief Description of GPS SPS Performance Parameters

The purpose of this section is to describe the GPS SPS performance parameters and the controls employed by the GPS Operational Control System (OCS) to manage performance against the performance standards.

System behavior is defined in terms of a series of performance parameters. These parameters are statistical in nature, to acknowledge the uncertainties inherent in GPS performance. The performance parameters dealt with in this Appendix are service availability, service reliability, and accuracy. The characteristics of each of these parameters must be considered to completely define the GPS civil performance envelope.

A-1.3.2.1 Service Availability

In previous documents, ***service availability*** was defined in terms of the percentage of time constellation geometry provides a Position Dilution of Precision (PDOP) of six or less. Service availability is inherently a predictive quantity, since it establishes an expectation of system performance rather than actual instantaneous behavior. The new definition for service availability includes not only the constellation geometry, but also the predicted URE contribution to user performance. Conceptually, the new definition says that the combination of constellation geometry and URE have to remain below a specified tolerance for at least a minimum percentage of the time. The predicted error level is scaled to a 95% level. Another refinement to the availability concept was to establish two availability definitions: one for horizontal performance (combination of horizontal position solution geometry and URE) and one for vertical (combination of vertical position solution geometry and URE).

A-1.3.2.2 Service Reliability

GPS can be used anywhere within the global service volume. A failure in a system with a global service volume affects 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 Signal-in-Space User Range Errors (SIS UREs) within a specified reliability error threshold, given the satellite is healthy and not broadcasting a URA indicating possible performance over the error threshold. A service reliability of 100% is achieved when no healthy satellite's SPS SIS URE exceeds the reliability error threshold over the sample interval without an indication to the user.

A-1.3.2.3 Accuracy

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 positioning accuracy is defined in the Performance Standard from three different perspectives:

- Positioning Accuracy,
- Time Transfer Accuracy, and
- Ranging Signal Accuracy (represented in this standard as User Range Error (URE))

Positioning accuracy represents how well the position solution conforms to "truth". Truth is defined to be any specified user location where the position is known, within acceptable error tolerances and with respect to an accepted coordinate system, such as the World Geodetic System 1984 (WGS84) Earth-Centered, Earth-Fixed (ECEF) Coordinate System. Factors which affect positioning accuracy include geometry and URE variations unique to a given user location and the sample interval over which measurements are taken.

Time transfer accuracy represents how well a time transfer service user can relate receiver time to Coordinated Universal Time (UTC) as disseminated by the United States Naval Observatory (USNO). The definition of time transfer has been modified for this edition of the SPS Performance Standard to represent performance from a time transfer user's perspective, as opposed to a positioning service user. The primary distinction is that a time transfer user operates from a known location and directly ensembles the measured range residuals from all satellites in view instead of mapping them through a position solution geometry.

Ranging signal accuracy represents the performance of the constellation in terms of User Range Error (URE). Other ranging signal accuracy parameters of interest to the civil community are range rate and range acceleration error. Previous documents established performance standards for these two parameters to serve as bounding conditions for Selective Availability (SA). With the removal of SA, these parameters are no longer explicitly provided as formal standards. The U.S. Government has instead established its intent to impose no artificial range rate or range acceleration errors. A description of current range rate and range acceleration error behaviors is provided in Section A-5.6.

A-1.3.2.4 The Four Elements of GPS Performance Control

Four core operational control mechanisms are used to manage GPS performance:

- Constellation slot definition and tolerances
- Constellation slot availability
- Constellation Signal-in-Space (SIS) User Range Error (URE)
- GPS-UTC (USNO) time scale difference management

Constellation slot management is the maintenance of each GPS satellite's orbit to within a specified tolerance, with tolerances established based on the satisfaction of a constellation geometry optimization criterion. Satellite availability management is the process of ensuring each satellite's availability to users is maximized, while supporting required maintenance and repair activities. Satellite URE management is the control of line-of-sight errors between each satellite and users within view of the satellite. GPS-UTC (USNO) time scale difference management is the process of monitoring and calibrating the bias between the GPS time scale and Coordinated Universal Time (UTC) as defined by the United States Naval Observatory (USNO).

SECTION A-2 GPS Operations Overview

The purpose of this section is to describe how four core operational control mechanisms are employed to sustain GPS performance in accordance with operational standards. GPS performance management practices may evolve over time in response to changing system behaviors or operating conditions.

The four core operational controls used to manage GPS performance are:

- Constellation slot definition and tolerances
- Constellation slot availability
- Signal-in-Space (SIS) User Range Error (URE)
- GPS-UTC (USNO) time scale difference management

The information provided in this section serves to provide users with background concerning the operations of the GPS constellation.

A-2.1 Constellation Slot Definition and Tolerances

The GPS constellation is a dynamic entity that is designed to provide consistent position solution geometry characteristics. The specific design goals of the GPS constellation were to:

1) Provide the maximum availability of optimum geometry on a global basis for a 24-satellite constellation, using the global four-satellite Position Dilution of Precision (PDOP) at a five-degree mask angle as the optimization criterion.
2) Maintain consistent ground tracks.
3) Minimize the effects on availability of removing any single satellite from service.
4) Define slot position tolerances such that no satellite requires more than one maneuver over any one-year interval to remain within its slot.

Obviously a satellite constellation is not a fixed entity in space and exhibits a range of dynamic behavior over its lifetime. This dynamic behavior begins with launch dispersions unique to each satellite and continues with satellite-unique orbit precession over the lifetime of the satellite. Stationkeeping maneuvers are conducted to compensate for orbit precession effects and maintain Groundtrack Equatorial Crossings (GECs), but orbit plane divergence from the nominal is unavoidable. To this end, two different sets of ephemeredes are presented in this section. The first set is the nominal constellation plan, illustrating the intent of the constellation design and the ground rules for maintaining the constellation. This set is representative of the nominal constellation slot assignments presented in the SPS Performance Standard, Section 3.1. The second set is an example of the current operational nominal constellation, with GECs adjusted to compensate for orbit plane dispersion. Orbital element sets are presented for the nominal constellation plan and the current nominal constellation in almanac form for ease of use. For comparison purposes, both sets are defined at the same epoch time.

A-2.1.1 Nominal Constellation Plan

The current architecture for the constellation identifies nominal orbit slots for a 24-satellite constellation and tolerances for establishing and maintaining satellites within the slots. Table A-2-1 identifies values for an almanac that is representative of the system nominal constellation plan defined in the SPS Performance Standard. The listed Mean Anomaly values (M_o) place the satellites at GECs consistent with the intent of the nominal constellation plan.

Table A-2-1. Nominal Constellation Plan, Time of Almanac: 9/24/2000 17:04:00.00

Orbit Slot	e	δi (1) (degrees)	Ω_{dotJ2} (deg/sec)	A (km)	Ω_o (2) (degrees)	ω (degrees)	M_o (degrees)
A1	0.000	1.000	-4.4874E-07	26559.7	162.374	0.000	82.826
A2	0.000	1.000	-4.4874E-07	26559.7	162.374	0.000	-23.514
A3	0.000	1.000	-4.4874E-07	26559.7	162.374	0.000	186.376
A4	0.000	1.000	-4.4874E-07	26559.7	162.374	0.000	-143.494
B1	0.000	1.000	-4.4874E-07	26559.7	-137.626	0.000	-104.344
B2	0.000	1.000	-4.4874E-07	26559.7	-137.626	0.000	-11.964
B3	0.000	1.000	-4.4874E-07	26559.7	-137.626	0.000	-235.324
B4	0.000	1.000	-4.4874E-07	26559.7	-137.626	0.000	19.076
C1	0.000	1.000	-4.4874E-07	26559.7	-77.626	0.000	-73.424
C2	0.000	1.000	-4.4874E-07	26559.7	-77.626	0.000	186.496
C3	0.000	1.000	-4.4874E-07	26559.7	-77.626	0.000	154.366
C4	0.000	1.000	-4.4874E-07	26559.7	-77.626	0.000	56.256
D1	0.000	1.000	-4.4874E-07	26559.7	-17.626	0.000	-50.074
D2	0.000	1.000	-4.4874E-07	26559.7	-17.626	0.000	-279.854
D3	0.000	1.000	-4.4874E-07	26559.7	-17.626	0.000	209.856
D4	0.000	1.000	-4.4874E-07	26559.7	-17.626	0.000	-17.944
E1	0.000	1.000	-4.4874E-07	26559.7	42.374	0.000	11.746
E2	0.000	1.000	-4.4874E-07	26559.7	42.374	0.000	-242.704
E3	0.000	1.000	-4.4874E-07	26559.7	42.374	0.000	-119.234
E4	0.000	1.000	-4.4874E-07	26559.7	42.374	0.000	-211.614
F1	0.000	1.000	-4.4874E-07	26559.7	102.374	0.000	53.586
F2	0.000	1.000	-4.4874E-07	26559.7	102.374	0.000	159.926
F3	0.000	1.000	-4.4874E-07	26559.7	102.374	0.000	-80.094
F4	0.000	1.000	-4.4874E-07	26559.7	102.374	0.000	-49.954

NOTE (1): δi is relative to 0.30 semi-circles (54 degrees)
NOTE (2): The (Ω_o) values place each satellite orbit at its respective mean constellation orbit plane

Tolerances/operational ranges for nominal orbit insertion and continuing orbit maintenance are as follows:

- Groundtrack Equatorial Crossing: ± 2°
- Eccentricity: 0.00 – 0.02
- Inclination: ± 3°
- Semi-major Axis: ± 50 kilometers for Block IIR, ± 17 kilometers for Block II/IIA
- Longitude of the Ascending Node: ± 2°
- Argument of Perigee: ± 180°

Note that orbit insertion error following launch can cause any of these parameters to exceed the required tolerance. Stationkeeping is not performed to maintain eccentricity or inclination.

A-2.1.2 Current Operations Nominal Constellation

The information presented in Table A-2-1 represents a set of constellation design objectives established before the launch of any of the current operational satellites. The term "current operations nominal constellation" is used to distinguish what is considered the "optimum" constellation using current on-orbit assets from the "nominal constellation plan" established in Table A-2-1. Table A-2-2 identifies values for an almanac that represents the current operations nominal constellation as of the epoch time. The current operations "nominal" constellation is defined based upon annual updates from the system operator. The current operations policy is to update target Geographic Longitude of the Ascending Nodes (GLANs) on a yearly basis, to compensate for the effects of nodal regression. As can be seen, parameters reflect the actual state of the current constellation, with variations evident in eccentricity, inclination, and semi-major axis based upon the launch insertion errors unique to each satellite.

Table A-2-2. Current Ops Nominal Constellation, Time of Almanac: 9/24/2000 17:04:00.00

Orbital Position	e	δi (1) (degrees)	Ω_{dot} (degrees/ second)	A (meters)	Ω_o (degrees)	ω (degrees)	M_o (degrees)
A1	0.0109	0.119	-4.499E-07	26,559,644	161.721	36.798	44.569
A2	0.0083	-0.296	-4.531E-07	26,561,421	159.421	-119.910	93.112
A3	0.0078	0.921	-4.414E-07	26,559,861	164.474	109.126	76.412
A4	0.0144	-0.039	-4.512E-07	26,557,536	160.671	-154.334	7.860
B1	0.0134	-0.518	-4.780E-07	26,559,121	-140.488	34.131	-140.091
B2	0.0054	0.087	-4.728E-07	26,558,935	-138.307	81.925	-95.396
B3	0.0204	-0.496	-4.754E-07	26,559,765	-141.277	-119.701	-120.109
B4	0.0023	-0.324	-4.761E-07	26,558,985	-140.141	12.779	4.019
C1	0.0070	0.257	-4.649E-07	26,559,448	-76.845	-134.773	58.320
C2	0.0013	-0.176	-4.741E-07	26,559,760	-79.314	46.897	137.004
C3	0.0096	0.329	-4.689E-07	26,561,731	-78.586	47.657	105.084
C4	0.0116	0.360	-4.643E-07	26,558,980	-78.608	-118.173	170.858
D1	0.0092	2.505	-4.315E-07	26,559,614	-15.094	-97.275	44.798
D2	0.0024	-1.043	-4.649E-07	26,559,322	-19.249	-163.471	-119.765
D3	0.0124	2.378	-4.335E-07	26,560,253	-11.104	173.130	35.480
D4	0.0052	1.931	-4.374E-07	26,558,804	-15.848	-30.998	11.065
E1	0.0025	0.956	-4.748E-07	26,560,183	42.858	129.677	-119.734
E2	0.0166	1.888	-4.656E-07	26,559,896	43.112	-144.564	-100.752
E3	0.0041	1.914	-4.669E-07	26,560,112	42.769	-1.198	-119.546
E4	0.0149	2.065	-4.643E-07	26,559,478	45.477	-107.795	-106.857
F1	0.0077	1.074	-4.649E-07	26,560,817	101.437	-108.860	159.710
F2	0.0123	1.259	-4.623E-07	26,558,930	103.077	8.663	149.701
F3	0.0022	1.328	-4.623E-07	26,541,449	102.760	-30.390	-51.701
F4	0.0049	1.091	-4.636E-07	26,559,765	104.050	-99.324	46.950

NOTE (1): δi is relative to 0.30 semi-circles (54 degrees)

Note that the constellation defined in Table A-2-2 represents the current "nominal" constellation only as of the identified epoch, although the target GLANs are as mentioned previously maintained for a one-year period. Figure A-2-1 illustrates how individual satellites are tracked against their respective GLAN targets to support stationkeeping maneuver planning. Note that insertion of new satellites into primary constellation slots will obviously change the nominal characteristics for that slot.

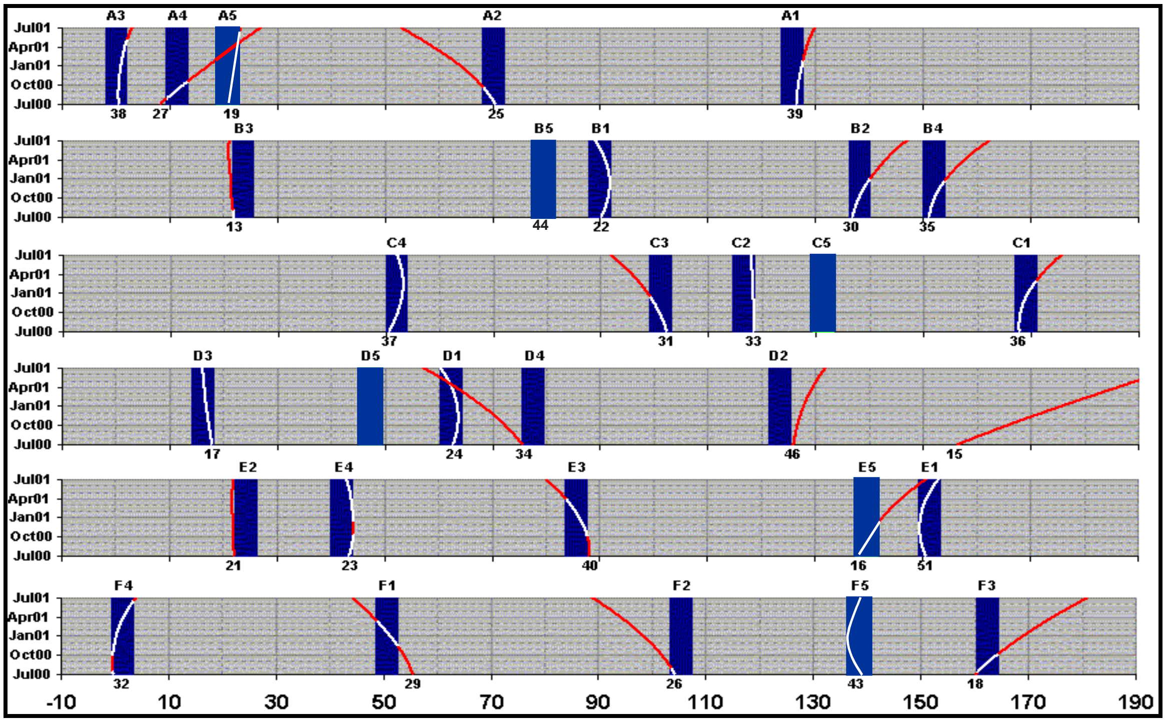


Figure A-2-1. Predicted GPS Constellation Geographic Longitude of Ascending Node Behavior (Courtesy 2SOPS)

An example of the type of analysis required to ensure new slot definitions conform to the Position Dilution of Precision (PDOP) optimization criterion is presented in Figure A-2-2. All-in-view position solution PDOP values are provided in comparison with the best four-satellite position solution PDOPs. The all-in-view PDOP values were provided to illustrate the fact their availability is always slightly better than the four-satellite PDOP values.

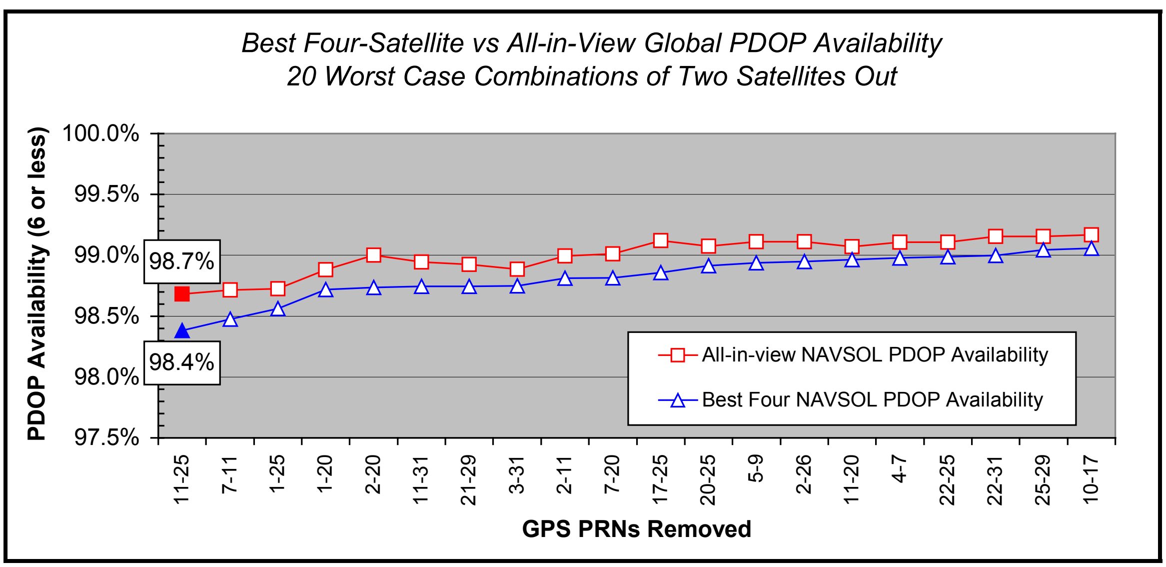


Figure A-2-2. Example of Current Global PDOP Optimization Criterion Analysis

A-2.1.3 Placement and Usage of On-orbit Spares

The GPS constellation is currently designed and optimized for 24 satellites. In an effort to guard against satellite failures and maintain a high probability of all 24 slots being populated, the U.S. Government may launch satellites into planes that are already fully populated. The criteria for where to launch a spare satellite focus primarily on the average age of the satellites in each plane, the projected health and status of each satellite, and whether or not a spare already exists in a given plane.

Retaining a spare satellite in an active state on-orbit has little or no impact on the operational life of the satellite. GPS on-orbit spares are therefore maintained as part of the operational constellation and are useable by the GPS user community. Performance standards are still, however, defined based upon the core 24-satellite constellation. Note that since spare satellites are not considered primary operational assets, the U.S. Government reserves the right to place them and employ them as necessary to support system development, test, and operational objectives. Any improvement in user performance that comes as a result of the placement of a spare satellite is regarded as a fortunate by-product of constellation management practices.

A-2.2 Constellation Slot Availability

Constellation slot availability is a function of two major factors:

- Satellite Reliability, Maintainability, and Availability (RMA) behavior over each satellite's lifetime, and
- Replacement timeline at the end-of-life for a satellite in a primary slot.

GPS satellites are designed to provide virtually continuous service over the lifetime of the satellite. Satellites do experience some downtime each year, due to scheduled events such as stationkeeping maneuvers, and due to random component failures. Table A-2-3 provides a comparison of actual versus theoretical RMA attributes for the Block II/IIA satellites since January 1994. Block IIR satellites have not yet had enough on-orbit operational time to support a proper RMA trend analysis, but their theoretical RMA characteristics are somewhat better than those of the Block II/IIA satellite. See Appendix B for definitions of terms used in Table A-2-3.

Table A-2-3. GPS Satellite RMA Performance Since IOC

GPS Satellite RMA Parameter: January 1994 – July 2000	Actual	Theoretical/Design
Total Forecast Downtime per SV per year (hrs)	35.6	NA
Total Scheduled Downtime per SV per year (hrs)	18.7	24
Total Unscheduled Downtime per SV per year (hrs)	39.3	64
Total Actual Downtime per SV per Year (hrs)	58.0	88
Satellite MTBF (hrs)	10,749.4	2,346.4
Satellite MTTR (hrs)	48.2	17.1
Satellite MTBDE (hrs)	3,255.9	1,528.8
Satellite MDT (hrs)	21.5	15.4
# Unscheduled SV Downing Events per SV per year	0.9	3.7
# Scheduled SV Downing Events per SV per year	1.9	2.0
# Total Average SV Downing Events per SV per year	2.7	5.7
Average SV Availability per year – Scheduled Downtime	**99.79%**	**99.73%**
Average SV Availability per year - All Downtime	**99.34%**	**99.00%**

Note that although the total downtime per satellite per year is less than the projected values based on satellite design, the Mean Down Time (MDT) is actually somewhat greater. The MDT statistic is skewed by extended downtimes for satellites that have reached their end-of-life, and by efforts from the constellation operators to get as much service as possible before declaring the satellite dead.

The replacement timeline for a failed satellite in a primary slot depends on whether or not a spare satellite is available in the appropriate plane. The current nominal timelines for replacing a failed satellite in a primary slot with a fully operational satellite are as follows:

- 30 days given an available on-orbit spare
- 120 days when a launch call is required

The intent of the U.S. Government is to minimize the probability that such a failure event occurs. If the system operator considers the prognosis on a satellite in a core slot marginal, a scheduled launch is targeted for that satellite's node, and the marginal satellite has historically been phased to a spare slot.

The intent of the U.S. Government is to manage the constellation such that it never drops below 22 healthy satellites in nominal slots. Figure A-2-3 illustrates the percentage of time historically the constellation has been comprised of a given number of healthy satellites.

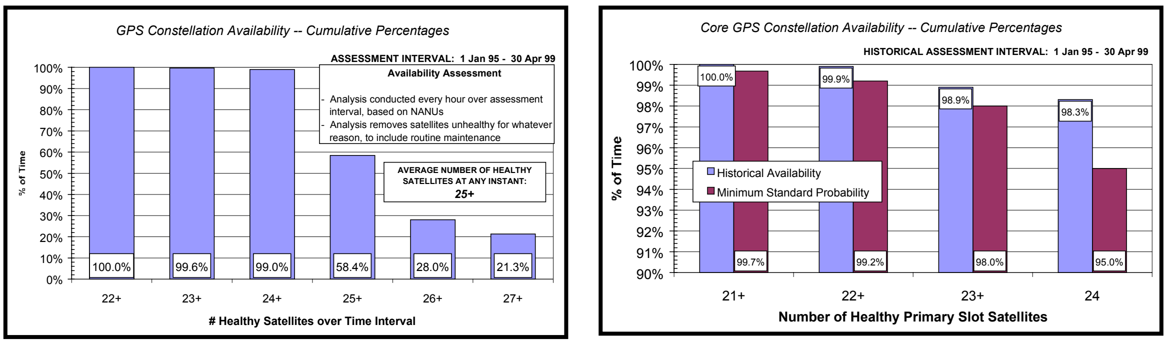


Figure A-2-3. GPS Constellation Size Distribution

In an effort to mitigate the potential impacts of satellite outages on constellation geometry and service availability, projections are made every month of global Dilution of Precision (DOP) patterns for the following month. These patterns are based on evaluating all permutations of two satellites removed from the constellation to ensure the system operator knows where its sensitivities lie in scheduling satellite maintenance. More refined projections are run in support of actual maintenance a few days ahead of the event as a further safeguard against unnecessary impacts on user service. If future impacts are identified, options are defined to mitigate the problem if possible. If mitigation is not possible, it is the intent of the U.S. Government to notify GPS users a minimum of 48 hours in advance of an anticipated service degradation.

A-2.3 SPS Signal-in-Space User Range Error

SPS Signal-in-Space (SIS) User Range Errors (UREs) are comprised of two basic elements:

- SIS PPS URE
  - ⇨ includes satellite clock and ephemeris prediction error, OCS state estimate process noise, and residual curve fit error, as well as negligible residual noise from the measurements themselves (to include small residual errors from the troposphere and ionosphere propagation effects correction process)
  - ⇨ does not include instantaneous single-frequency ionosphere model errors, troposphere model errors, receiver noise or multipath effects
- C/A to P(Y) Code Phase Bias – includes satellite unique offsets as measured by the Jet Propulsion Laboratory (JPL)

Figure A-2-4 illustrates the PPS SIS URE trend over the past several years. The OCS uses the Estimated Range Deviation (ERD) quantity as its metric for monitoring PPS SIS UREs. Performance as of April 2001 across the constellation was 1.4 meters Root Mean Square (RMS), following the general trend witnessed over the past three years. Performance has gradually improved as older Block II satellites leave the constellation and newer Block IIR satellites with clocks exhibiting better short-term stability (to date) enter service.

Current constellation URE performance is driven by the OCS upload policy. Currently the OCS schedules one upload per day for each satellite, with a contingency upload executed if the instantaneous PPS SIS URE value exceeds three meters. This policy is adjusted depending on factors such as changing satellite clock stability characteristics and OCS resource status.

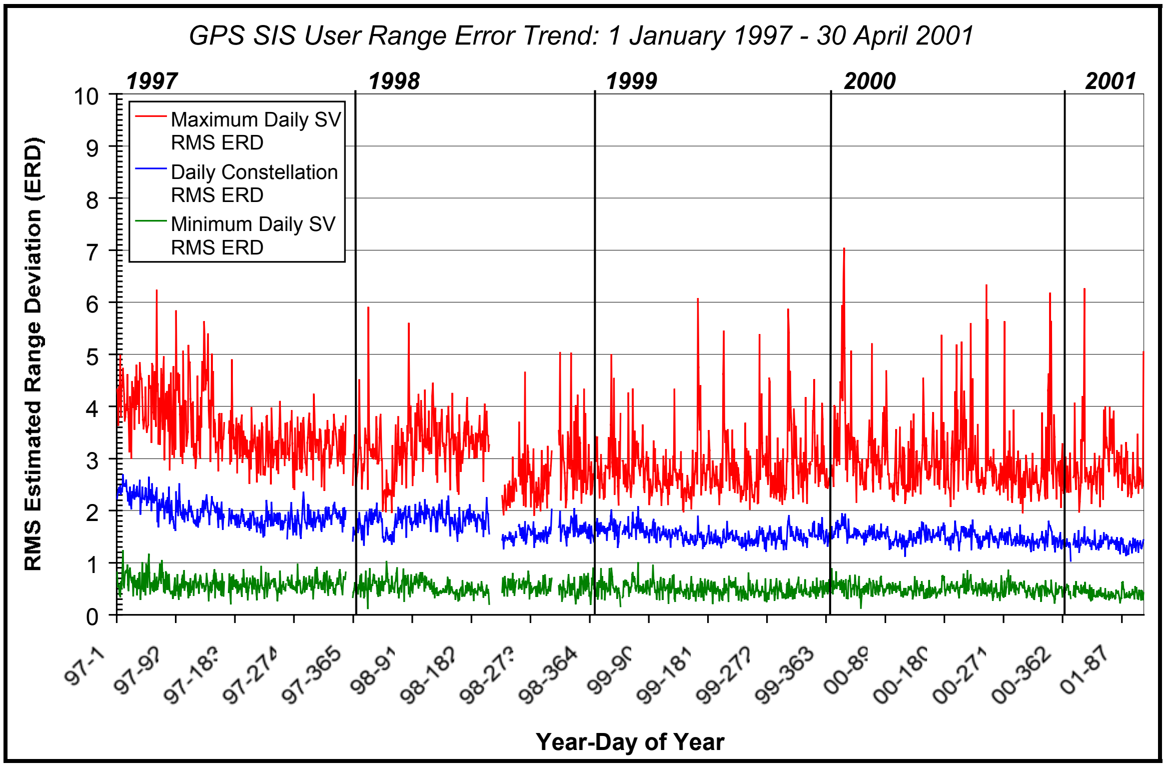


Figure A-2-4. PPS SIS URE Historical Trend

When defining SPS UREs, it is necessary to include the effects of C/A to P(Y) code phase biases for each satellite and a residual noise value of one nanosecond (1σ) to represent uncertainties in Jet Propulsion Laboratory (JPL) measurements of T_{GD} (the estimated group delay differential as defined in ICD-GPS-200C). The C/A to P(Y) code phase bias information used in the analysis was obtained from JPL via the Aerospace Corporation and is presented in Table A-2-4. JPL provides updates to the values in Table A-2-4 on a quarterly basis and whenever a new satellite is launched or an on-orbit satellite redundancy configuration is changed.

Figure A-2-5 contrasts PPS and SPS SIS URE statistic values over the one-week interval of 10-17 June 2000.

The most significant contributor to URE as experienced by the end user is generally the error in the ionosphere single-frequency model (as defined in ICD-GPS-200C). Model coefficient values are selected based on the current solar flux density, and placed in each navigation upload. Errors in the single-frequency model due to the coefficients or limitations in the model itself are not within the control of the U.S. Government, and are not included in the SPS SIS URE performance standard.

Table A-2-4. JPL C/A to P(Y) Code Phase Bias Information – May 2000

PRN	Average (m)	High Value (m)	Low Value (m)	Spread (m)	Variance (m^2)	PRN	Average (m)	High Value (m)	Low Value (m)	Spread (m)	Variance (m^2)
1	-0.105	0.04	-0.23	0.27	0.053	17	-0.329	-0.16	-0.45	0.29	0.066
2	-0.347	-0.2	-0.45	0.25	0.05	18	-0.004	0.14	-0.12	0.26	0.057
3	0.011	0.17	-0.08	0.26	0.051	19	0.085	0.23	-0.02	0.25	0.056
4	0.388	0.53	0.29	0.24	0.051	21	-0.14	0.01	-0.24	0.25	0.052
5	-0.223	-0.07	-0.35	0.28	0.052	22	-0.48	-0.33	-0.58	0.24	0.052
6	0.137	0.3	0.03	0.27	0.059	23	-0.178	-0.05	-0.27	0.22	0.049
7	-0.376	-0.04	-0.5	0.46	0.077	24	0.064	0.21	-0.04	0.25	0.052
8	-0.291	-0.13	-0.4	0.26	0.055	25	0.215	0.38	0.09	0.29	0.064
9	0.084	0.25	-0.04	0.29	0.061	26	0.369	0.52	0.28	0.24	0.049
10	-0.556	-0.41	-0.65	0.24	0.051	27	-0.033	0.12	-0.16	0.28	0.056
13	0.485	0.63	0.4	0.24	0.049	29	0.257	0.4	0.17	0.23	0.051
14	0.088	0.23	-0.03	0.27	0.052	30	0.498	0.64	0.4	0.24	0.049
15	-0.375	-0.23	-0.48	0.25	0.053	31	-0.223	-0.08	-0.32	0.24	0.052
16	-0.26	-0.12	-0.36	0.24	0.051						

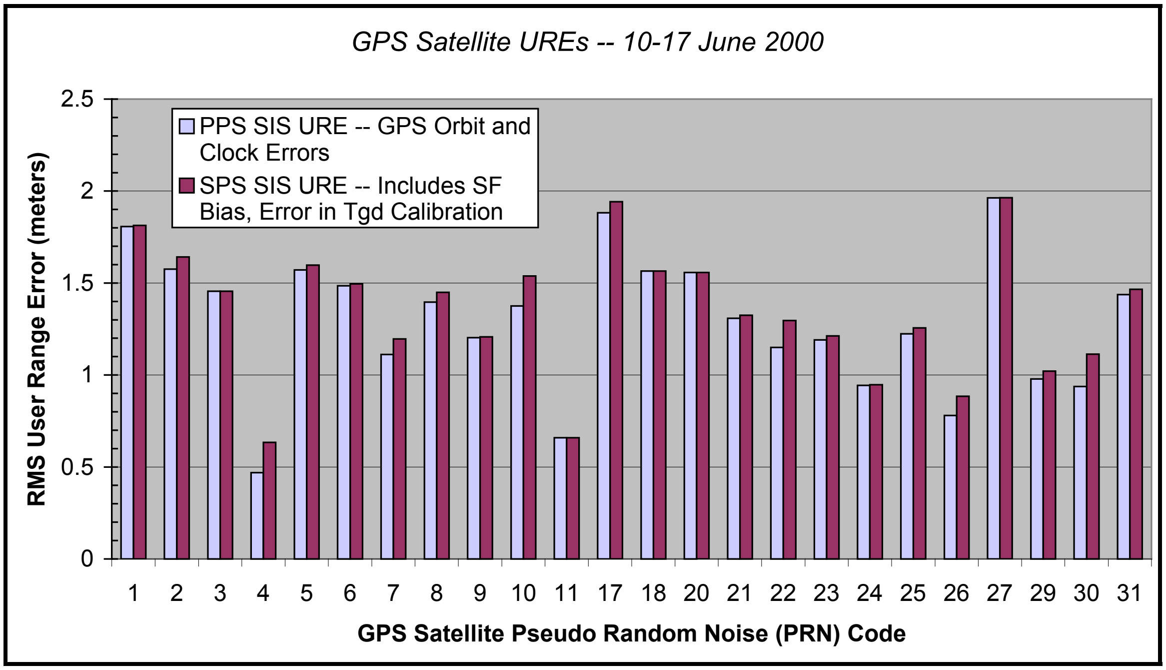


Figure A-2-5. GPS PPS and SPS SIS URE Performance -- 10-17 June 2000

A-2.4 GPS-UTC (USNO) Time Scale Difference Management

An estimate of the offset between GPS time and UTC as defined by the USNO is provided in each satellite's navigation message. The system operator interfaces on a daily basis with the USNO to obtain the USNO's measurement of this offset. The daily estimates are inputted to the MCS where they are used to project forward a prediction of the offset over the period of each navigation upload. The system operator also uses the estimates for adjusting GPS time to ensure the offset relative to UTC (USNO) does not deviate beyond operational tolerances.

SECTION A-3 Service Availability Characteristics

This section describes expected GPS service availability characteristics and provides the user with information concerning service availability patterns on a global average and worst site basis. Service availability varies slightly over time due to routine satellite maintenance requirements, constellation drift, and URE performance variations.

Service availability is described in terms of how it varies due to several different factors:

- Elevation mask angle
- Type of navigation solution (four-satellite versus all-in-view)
- All variations of one and two satellites removed from the current ops nominal 24-satellite constellation
- Satellite orbit position variations relative to nominal slot assignments
- Constellation RMS SPS SIS User Range Error

The section ends with a description of “normal” SPS service availability performance over the month of June 2000.

A-3.1 Effects of Varying Mask Angle on Service Availability

Receivers employ a variety of different elevation mask angles, depending on the application. The information presented in Figure A-3-1 and Figure A-3-2 show the effect varying elevation mask angles has on service availability, for an all-in-view receiver and a four-satellite solution receiver, respectively.

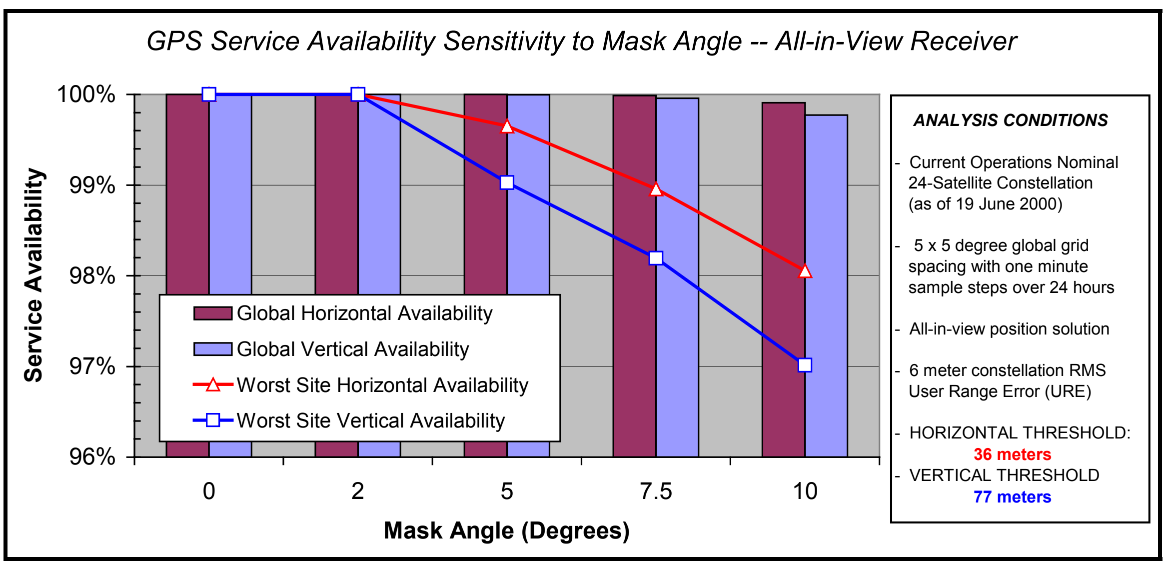


Figure A-3-1. Mask Angle Variation Effect -- All-in-View Receiver

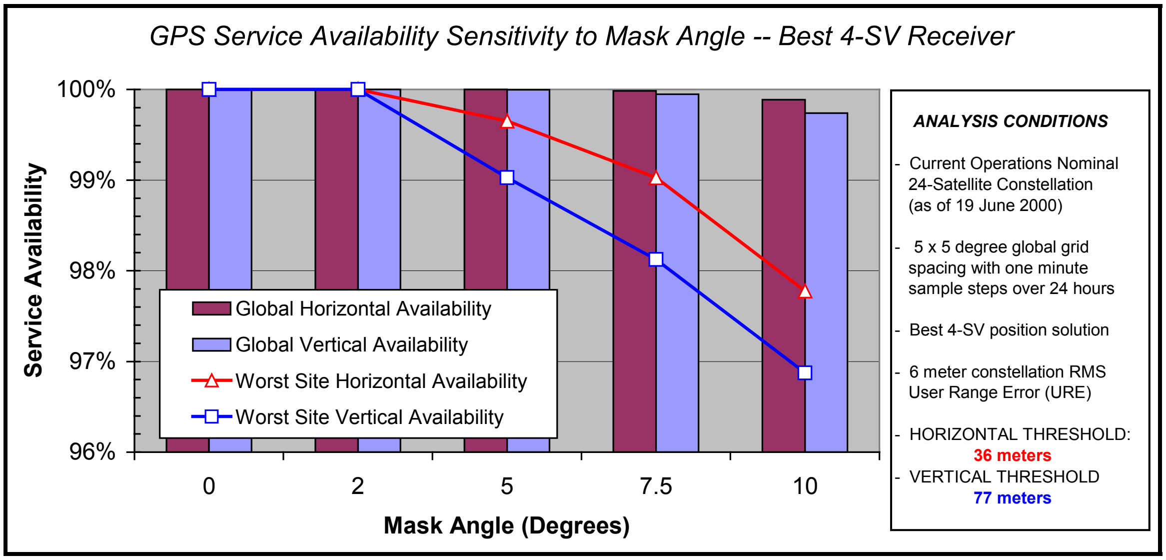


Figure A-3-2. Mask Angle Variation Effect -- Best Four Satellite Receiver

As shown in the figures, mask angle variations do not have a significant effect on global availability with a fully healthy constellation. Worst-case sites become significantly worse after the five-degree case. In the nominal constellation analysis, no occurrences of less than four satellites were observed, even at a ten-degree elevation mask. However, the number of sites experiencing less than four satellites climbs rapidly with increasing mask angle as individual or pairs of satellites are removed.

Note that variations of elevation angle mask do not apparently have a significantly different impact between four-satellite and all-in-view position solutions. This is probably due to the fact that the marginal geometries at the tail of the distribution have very few satellites in view. This indicates that the worst-case four-satellite and all-in-view position solutions are virtually identical.

A-3.2 Orbital Variation Effects on Service Availability

In Section A-2.1.1, a tolerance of ± 2° was established for each satellite orbit's GEC/LAN. An analysis of satellite LAN variation within the specified tolerance indicates that satellite movement within the LAN tolerances has nil effect on global service availability, and impacts worst site availability by less than one percent in the worst case examined.

A-3.3 Satellite Outage Effects on Service Availability

The most common reason for variations in service availability is the routine removal of a satellite for maintenance, or less commonly in response to a component failure. Analysis of the single-satellite out case demonstrates a minimal impact on service availability. Since one of the constellation design objectives was to minimize the effects of removing a single satellite from the constellation, this is a reasonable result.

A routine maintenance event coupled with a random failure in another satellite can result in a two-satellite out case. Position service geometry can be degraded significantly when certain pairs of satellites are removed from service, as shown in Figure A-3-3. Note that the impact of removing any pair of satellites is not static, but will vary as the constellation drifts.

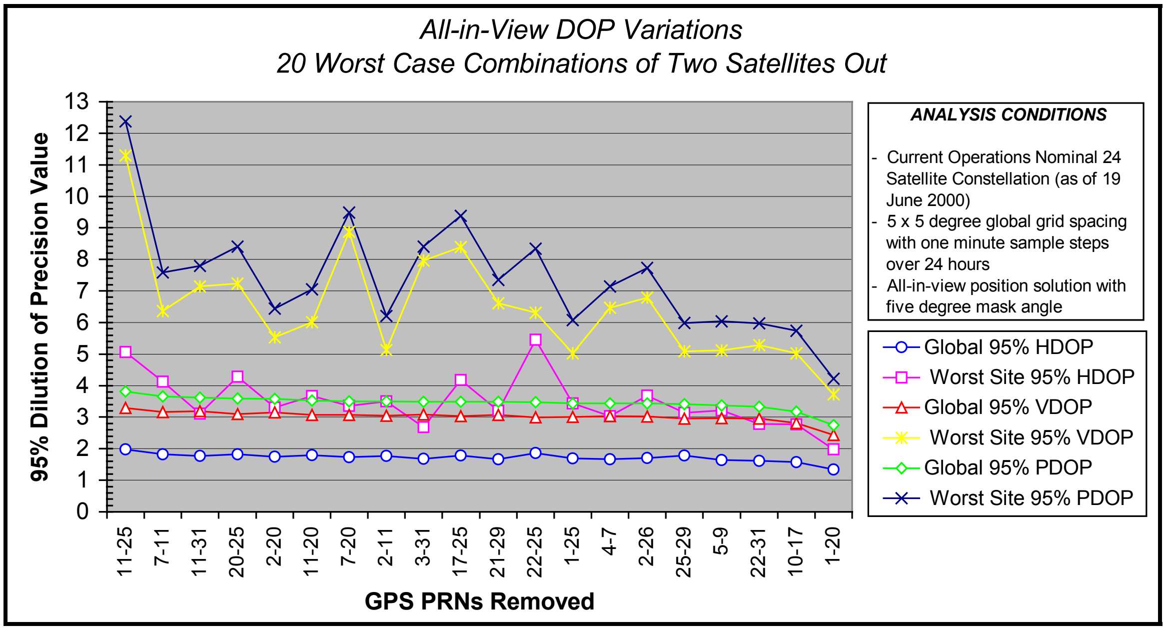


Figure A-3-3. Worst-Case DOP Values with Two Satellites Out

Figure A-3-4 and Figure A-3-5 represent the worst-case impacts on horizontal and vertical service availability of the 276 possible two-satellites out permutations. The results vary from almost no impact to an almost 9% reduction in worst-site vertical availability, for the worst-case combination of two satellites removed.

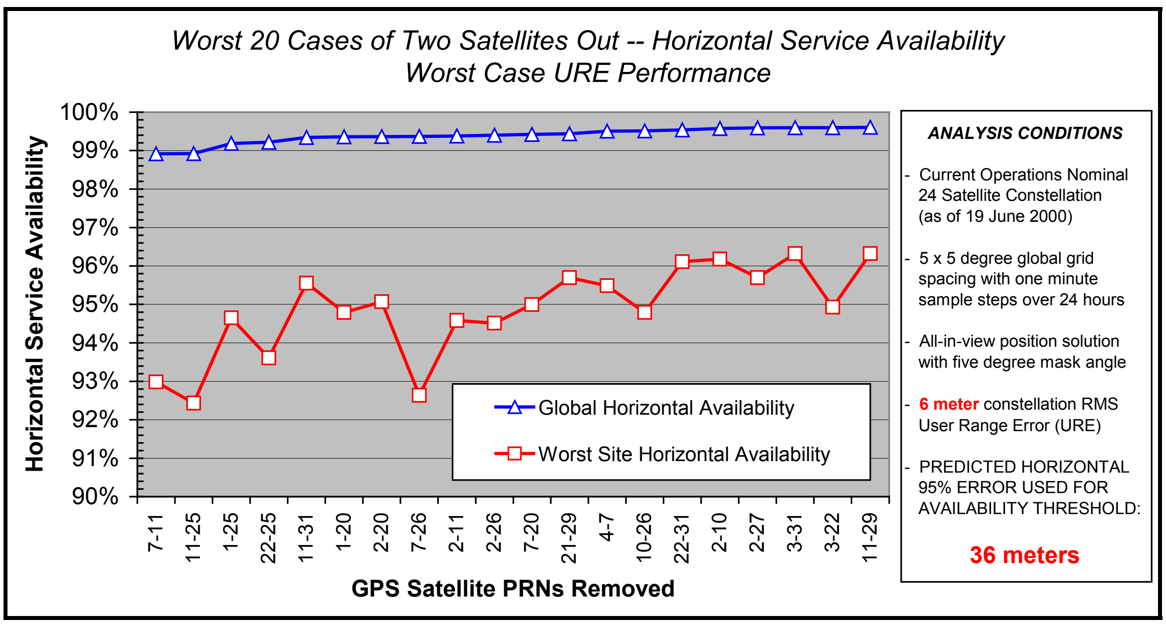


Figure A-3-4. GPS Horizontal Availability – Two Satellites Out

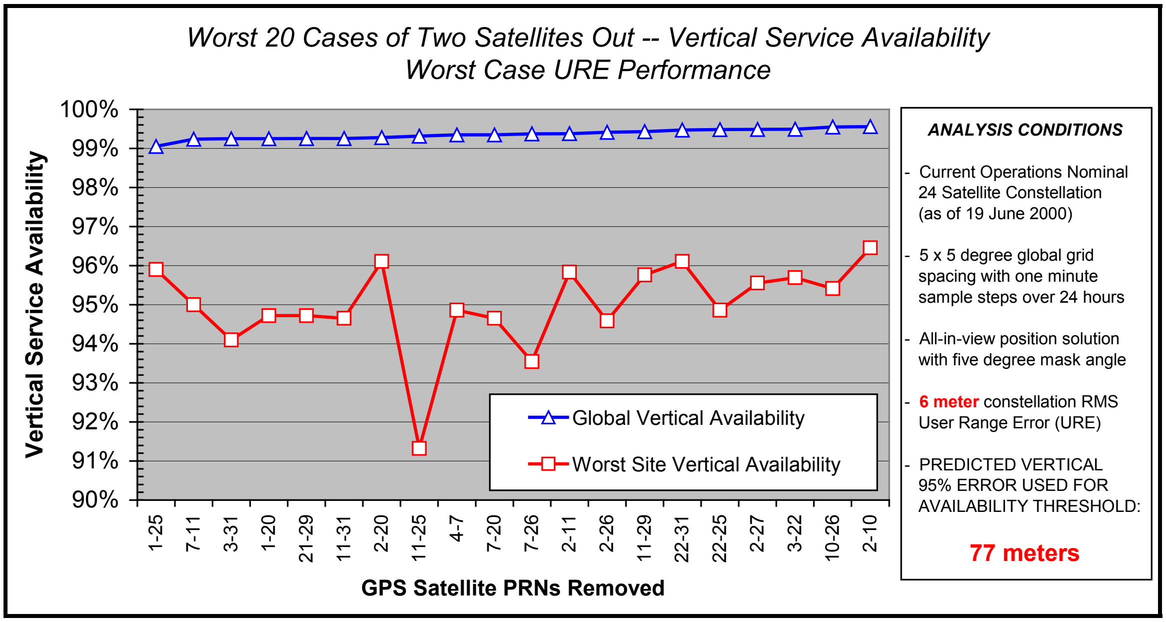


Figure A-3-5. GPS Vertical Availability – Two Satellites Out

Perhaps more important than the degradation of constellation geometry is the possibility of "DOP holes", periods of time where the solution geometry is too marginal to use or not enough satellites are in view to generate an unaided solution. Periods of time up to 39 minutes in duration with less than four satellites were observed for some locations in the worst-case two-satellite out combination. In the worst-case combination, 13% of the world experienced periods of less than four satellites visible. For those locations that did experience less than four satellites with the worst-case 22-satellite constellation, the average amount of time was approximately seven minutes. Since this analysis was conducted with a five-degree mask angle, users can anticipate significantly worse effects when using mask angles greater than five degrees in the unlikely event the constellation degrades to 22 satellites.

A-3.4 SIS URE Variation Effects on Service Availability

Given a nominal constellation of 24 or more satellites, service availability can vary considerably based on variations in constellation URE performance. This variation can become even more significant when geometry is degraded to the worst-case conditions, as illustrated in Figure A-3-6 and Figure A-3-7.

As shown in the figures, a constellation RMS URE of approximately 6 meters in a worst-case geometry scenario will by definition still support the service availability performance standard. With geometry variations over time, the maximum constellation RMS URE that supports the service availability may vary slightly. Given continuing consistency in the GPS program baseline and stability in managing constellation URE performance, this worst-case scenario is considered extremely unlikely to occur.

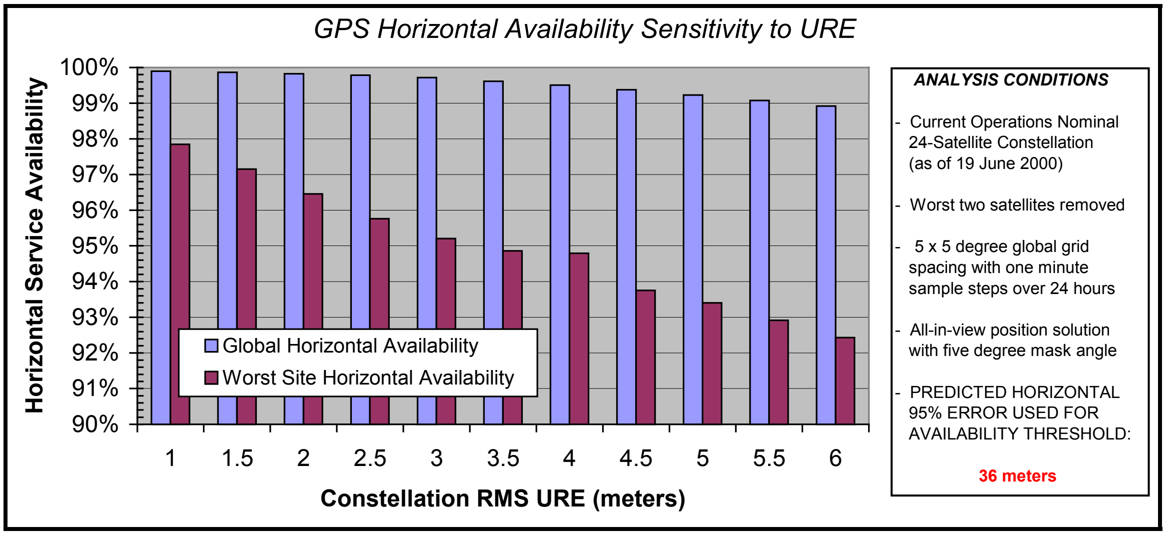


Figure A-3-6. Horizontal Service Availability Sensitivity to URE, Worst-Case Geometry

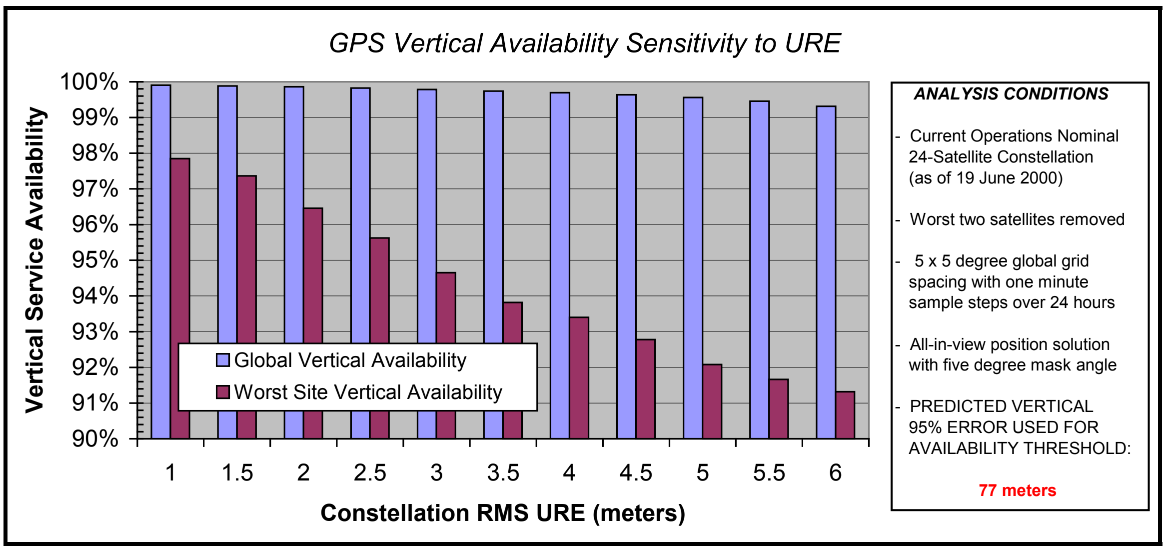


Figure A-3-7. Vertical Service Availability Sensitivity to URE, Worst-Case Geometry

A-3.5 Representative Service Availability Characteristics

As seen in Figure A-3-8, more than eight satellites are on average visible at the average location with the current operations nominal 24-satellite constellation. In the nominal 24-satellite case, less than six satellites are in view less than 0.1% of the time on average. With the current operational constellation, more than nine satellites are generally visible on a global basis. In the rare event the constellation is reduced to a worst-case 22 satellites, the average location will still see an average of seven satellites at any given time.

With the normal range of satellite availability and UREs across the constellation, availability is generally much better than the performance standards, as shown in Figure A-3-9 and Figure A-3-10. Both the global and worst-case site availability values are generally close to or at 100%. As satellites were removed from service later in the month, accuracy degraded slightly, but not enough to degrade service availability.

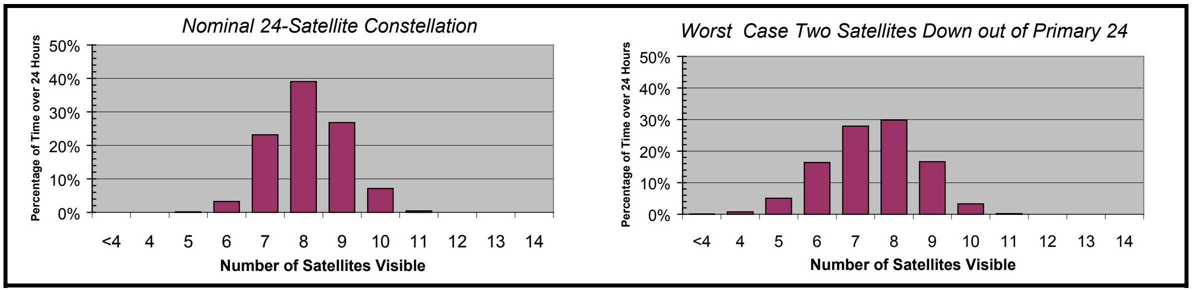


Figure A-3-8. Range of Average Global Satellite Visibility Distributions

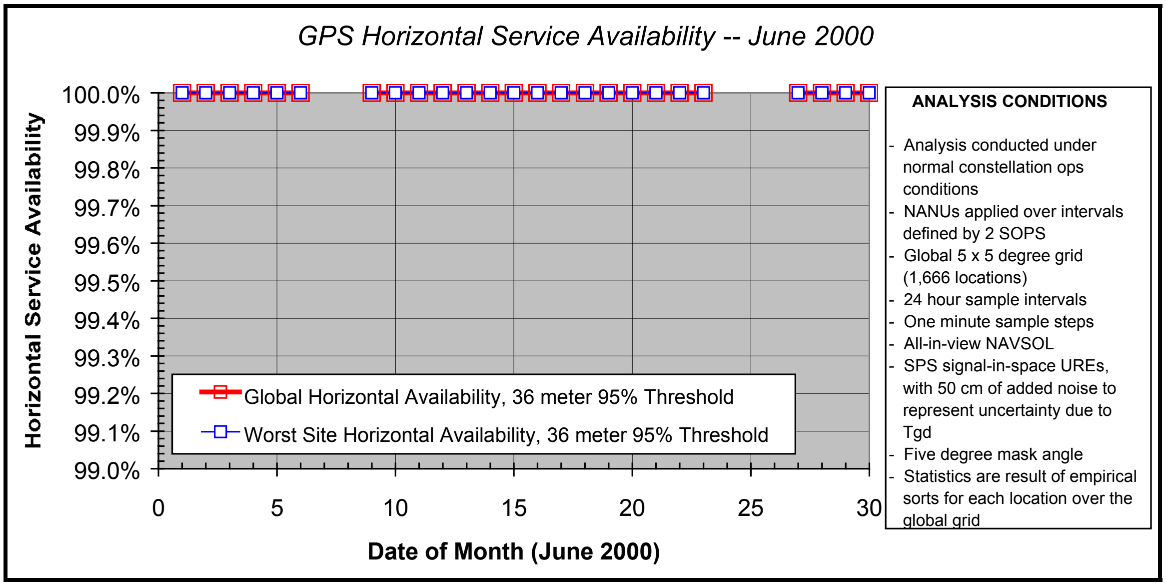


Figure A-3-9. Typical Example of GPS SPS Horizontal Availability – June 2000

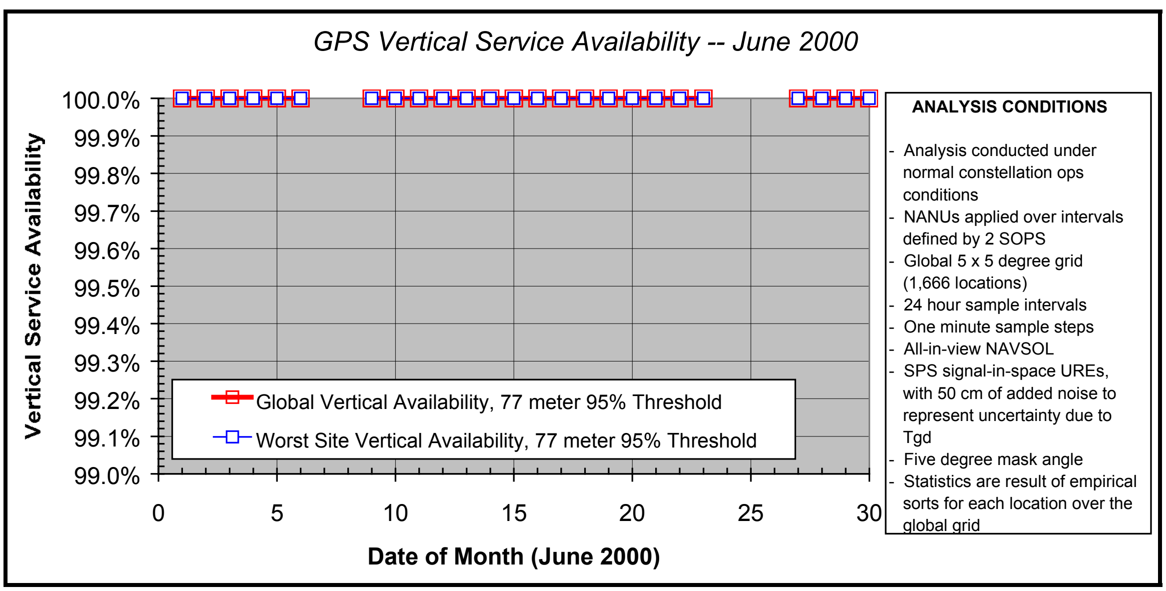


Figure A-3-10. Typical Example of GPS SPS Vertical Availability – June 2000

SECTION A-4 Service Reliability Characteristics

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

A-4.1 Reliability Threshold Selection

As defined in Section 1.4, service reliability is the measure of how consistently GPS User Range Error (URE) 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 URE characteristics is provided in Section A-2.3. The Not-to-Exceed (NTE) value must be larger than the practical limit on normal GPS URE performance. The largest URE that is typically experienced under normal operating conditions is approximately 10 meters. A value of 30 meters was chosen as the reliability threshold because it is sufficiently outside the normal URE 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 non-precision approach operations.

A-4.2 GPS Service Failure Characteristics

A service failure is defined to be a departure from nominal system ranging accuracy that causes the SPS instantaneous ranging error of a healthy satellite to exceed 30 meters while the User Range Accuracy (URA) multiplied out to 4.42 standard deviations indicates less than 30 meters. An occurrence of this behavior is directly due to a failure somewhere in the GPS ranging signal control and generation process. The characteristics of a service failure and the factors that 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.

A-4.2.1 Failure Frequency Estimate

The GPS satellite service failure history over the past several years indicates a very low service failure rate. However, when a service failure does occur, it can result in extremely large range and/or range rate 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 an average of three service failures per year. 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.

A-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, and
- Control Segment ground antenna coverage and availability.

The combination of these factors results in a conservative maximum failure 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. The nominal failure response time, taking into consideration a favorable combination of the above factors, is on the order of 30-45 minutes.

A-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 three types:

- Insidious, long-term (day or more to manifest themselves) performance deviations,
- Catastrophic, almost instantaneous failures, or
- Short-term transients.

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 code and carrier generation hardware failures. These failures, in general, result in very rapid ranging signal error growth -- range errors can grow to several thousand meters in a very short period of time. One example of 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.

Short-term transients can last a few seconds and are characterized either by a short transition into and out of non-standard code, or by rapid changes in ranging signal phase. Transient behaviors are discussed in more detail in Section A-4.4.

A-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 that can see it is approximately three hours. 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.

A-4.3 Expected Service Reliability Characteristics

When the system is performing nominally, no satellite's instantaneous URE will ever reach the service reliability threshold. Service reliability on those days where GPS does not experience a service failure is 100%.

The estimated maximum of three 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. 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 99.94%.

A-4.4 Current Experience with Transient Satellite Behaviors

GPS in general experiences steady state operations with very low levels of range rate and range acceleration errors. Infrequently, steady state operations are disturbed. For instance, whenever an upload occurs an instantaneous change in transmitted satellite position will cause an instantaneous offset in the apparent range to the satellite, sometimes by several meters. Other transients can also occur, and are the focus of discussions in this section.

GPS Block II and Block IIA satellites occasionally exhibit anomalous behavior in signal transmission that directly affects GPS SPS users. The anomalies occur as a result of a timing problem in the Block II and IIA satellites and occur on approximately 36% of all Block II navigation uploads. Occurrence on Block IIA satellites is rare, happening approximately once per month. The anomaly has not occurred on Block IIR satellites. When the anomaly occurs, the GPS satellite typically broadcasts Non-standard C/A Code (NSC). NSC is a code sequence reserved specifically for satellite failure conditions and is meant to ensure users cannot track through a failure detected by a GPS satellite.

The occurrence of transient signal behaviors in Block II and Block IIA satellites has two effects on SPS users:

- Receivers can experience a loss of signal availability during the time of the outage. In most cases the effect on the receiver is far longer than the duration of the outage on the satellite.
- Receivers can exhibit large code and phase jumps at the onset of the outages.

Following is an analysis of behaviors for several selected days. This is intended to familiarize the GPS user with the characteristics of the behavior for various receiver types.

On June 10, 1998, a double outage occurred on PRN 16 signal (the signal transitioned to non-standard code, then returned to standard C/A, then transitioned back to non-standard code, then transitioned back to standard C/A). This event was observed with two different dual-frequency GPS receivers, although the response of each receiver differed. One receiver exhibited large spikes in code and carrier phase, while the other did not. Figure A-4-1 illustrates the anomaly's effect on each of the two receivers.

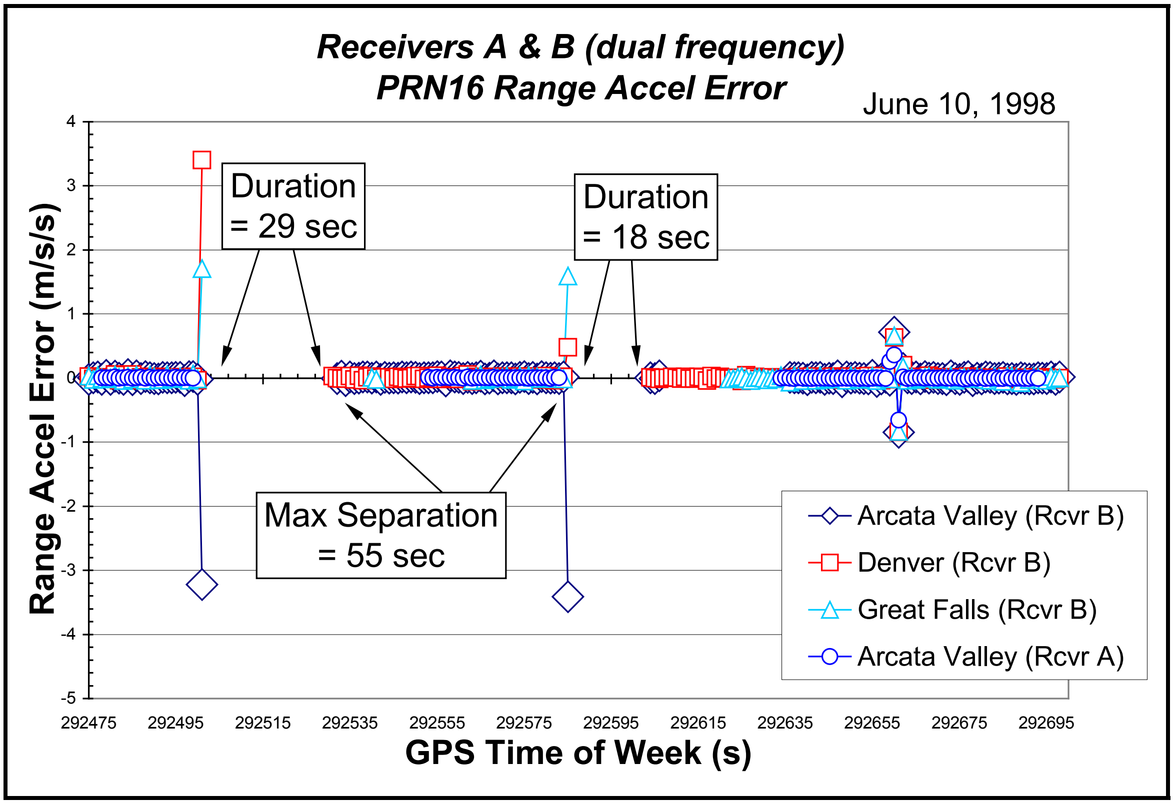


Figure A-4-1. Dual-Frequency Receiver Response (PRN 16 Anomaly)

On November 26, 1998, a single outage occurred on PRN 15. Figure A-4-2 shows the range acceleration error experienced by three different dual-frequency receivers at the time of the outage. The receivers, all of the same receiver type, exhibited a large range acceleration error at the onset of each outage, two of which have positive sense and the third negative sense. The magnitudes vary, but nearly all of them have magnitudes well over 1500 mm/s^2. A separate receiver type did not exhibit a magnitude spike at either of the outages. Furthermore, in each of the outages, this receiver took longer to reacquire the signal than any of the other receiver types.

Figure A-4-3 shows a six-second outage for PRN 19 on November 2, 1998, experienced by a 6-channel, single-frequency receiver. The C/NO value was used to determine the timing and duration of the outages. Under normal operation, the receiver dedicates its first five channels to each tracking a single satellite signal, leaving the sixth channel to multiplex track three other signals. The multiplex track, however, is conducted by tracking only two signals per second. For example for signals X, Y, and Z, the tracking each second is represented by XY, XZ, YZ, XY, XZ, YZ, and so on. In this way the receiver is able to track eight satellites with only six channels.

An interesting behavior occurred after the receiver reacquired the signal following the outage: the PRN was removed from the position solution set and reassigned to the multiplexing sixth channel. This continued for a period of five minutes before the PRN was returned to the position solution set.

The behavior of a 12-channel, single-frequency receiver was observed for the outage that occurred on PRN 15 on November 26, 1998. Figure A-4-4 shows C/NO values for the channel tracking PRN 15. At the time of the three outages, the channel substituted PRN 31 to be tracked, then returned quickly (44 seconds for the first outage, 8 seconds for the second, and 16 seconds for the third) to track PRN 15.

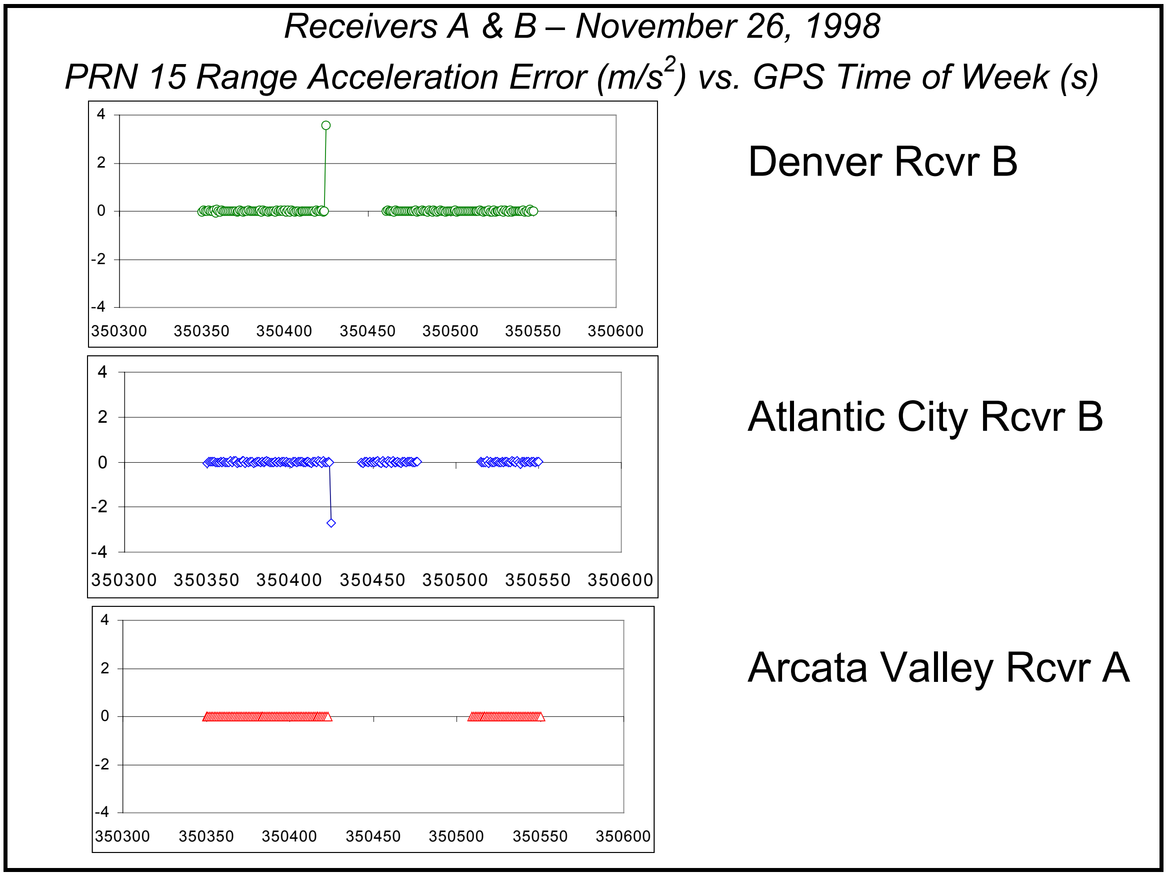


Figure A-4-2. Dual-Frequency Receiver Response (PRN 15 Anomaly)

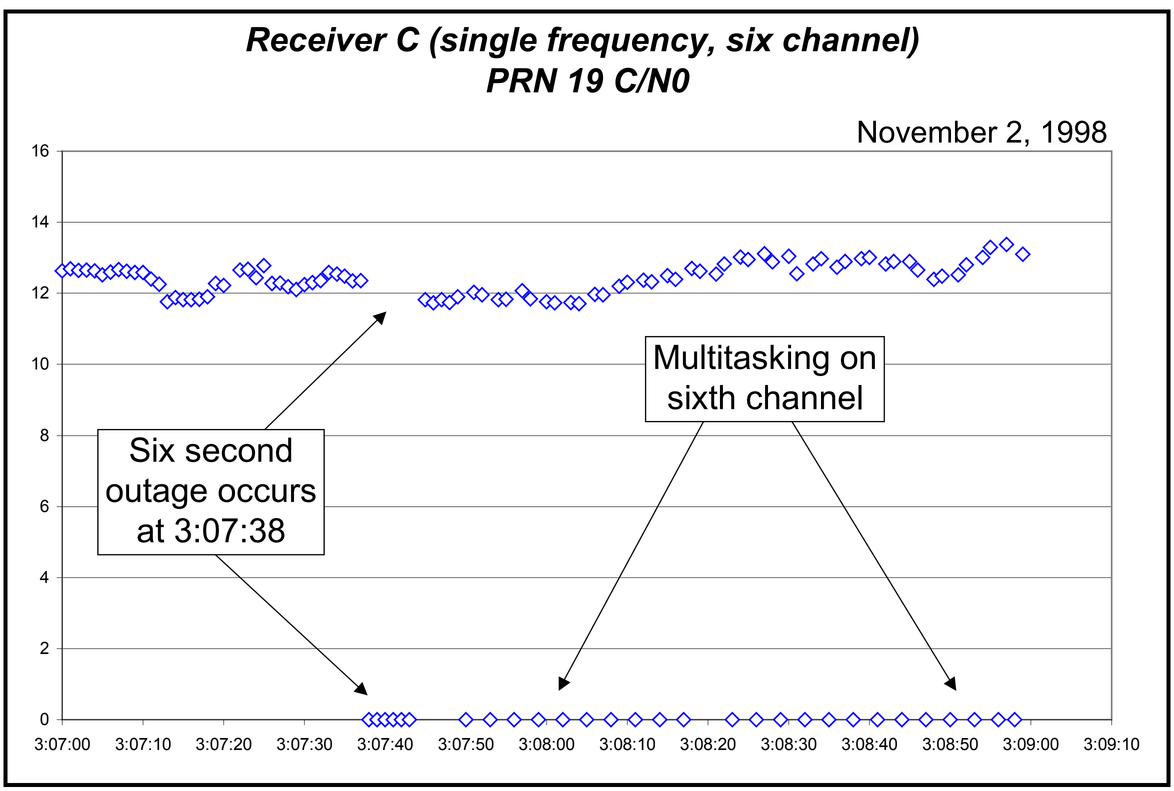


Figure A-4-3. Single-Frequency, 6-Channel Receiver Response (PRN19 Anomaly)

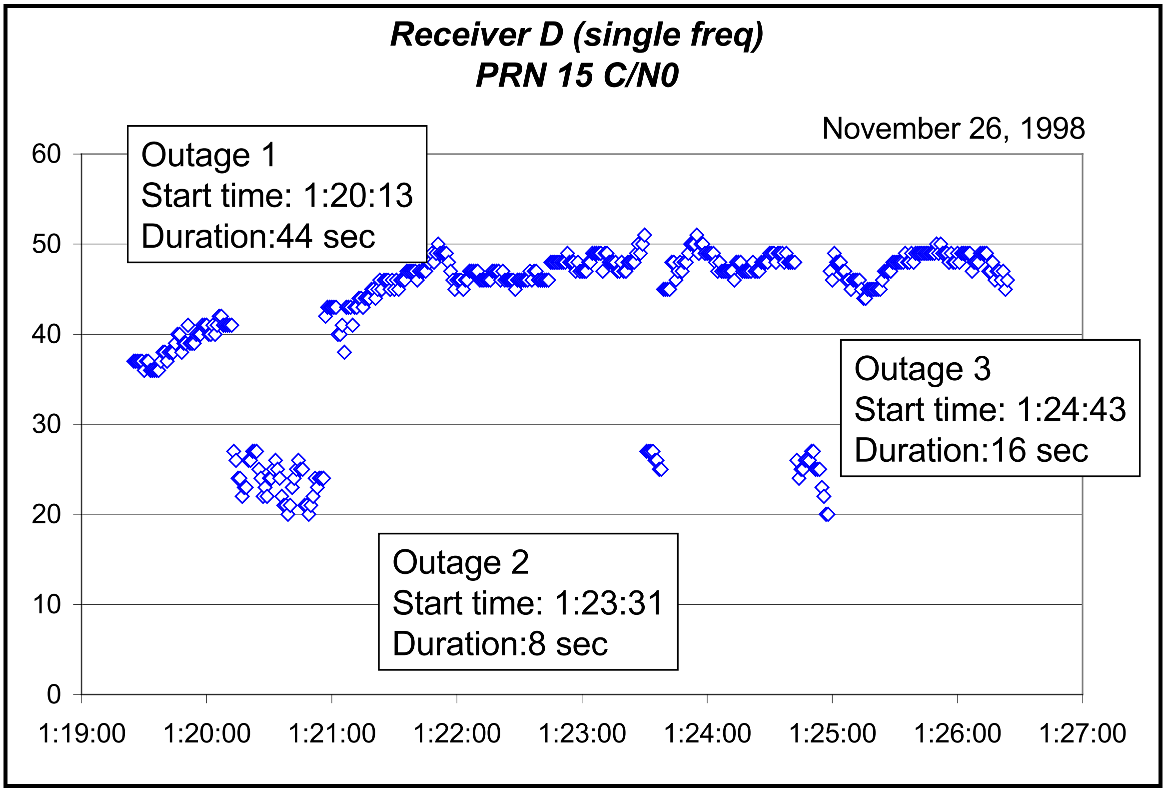


Figure A-4-4. Single-Frequency, 12-Channel Receiver Response (PRN 15 Anomaly)

SECTION A-5 Accuracy Characteristics

GPS SPS accuracy has improved tremendously since the use of Selective Availability (SA) was terminated. This section provides some insight into current accuracy characteristics in the absence of SA. Since the new SPS standards focus on Signal-in-Space (SIS) performance, initial discussions are framed in like manner. The discussion begins with an assessment of SIS SPS accuracy as a function of geographic location. Performance with combinations of two satellites removed is then discussed. SIS SPS positioning accuracy for the month of June 2000 is presented to illustrate observed daily performance variations. The section continues with a discussion of SIS time transfer performance.

The purpose of standards is to establish levels of performance against which a service provider will commit to operating a service. The SIS basis of the GPS SPS standards makes it a straightforward proposition to manage performance in terms of parameters under direct operational control. Although this standard definition approach has significant advantages in managing GPS performance, the standards cover only a portion of the total service an SPS user will experience. To mitigate this limitation in the standards definition, estimates are provided in Section A-5.5 of end user performance behaviors a single-frequency receiver may experience on an "average" day during solar maximum.

Two final aspects of accuracy of concern to civil users and in particularly differential service providers are range rate error and range acceleration error. Previous documents provided performance standards for these two parameters that reflected limits on the contributions of SA. With the termination of SA, users experience range rate error and range acceleration error behaviors that are primarily products of the receiver environment, with infrequent transients due to satellite navigation uploads or internal satellite design idiosyncrasies (discussed in Section A-4.4). The discussion in Section A-5.6 focuses on steady state characteristics of range rate and range acceleration error.

A-5.1 Geographic Variations in SPS SIS Positioning Errors

GPS position errors change as a function of latitude primarily due to constellation geometry, as shown in Figure A-5-1. As seen in Figure A-5-1, performance can be asymmetric between Southern and Northern latitudes. This asymmetry is caused by variations in URE due to satellite upload patterns, and variations in constellation geometry due to short-term satellite maintenance outages. Vertical accuracy is affected significantly more by latitude than horizontal error, due to the nature of the constellation geometry. Vertical accuracy suffers significantly above approximately 55° latitude (north or south) due to the lack of satellites at high elevation angles over the poles. Horizontal accuracy degrades mildly at mid-latitudes due to worsening horizontal geometry as latitude increases. However, horizontal accuracy begins to improve above approximately 45° latitude (north or south) as satellites visible from the other side of the Earth begin to enter into the position solution geometry.

Figure A-5-2 illustrates how accuracy varies as a function of longitude. The primary element in longitudinal variation of accuracy is the navigation upload patterns of the GPS satellites. A large percentage of satellites are uploaded over the continental United States or shortly before the satellites enter visibility over Europe. This trend can be seen very clearly in the vertical component in Figure A-5-2 and less clearly in the horizontal component.

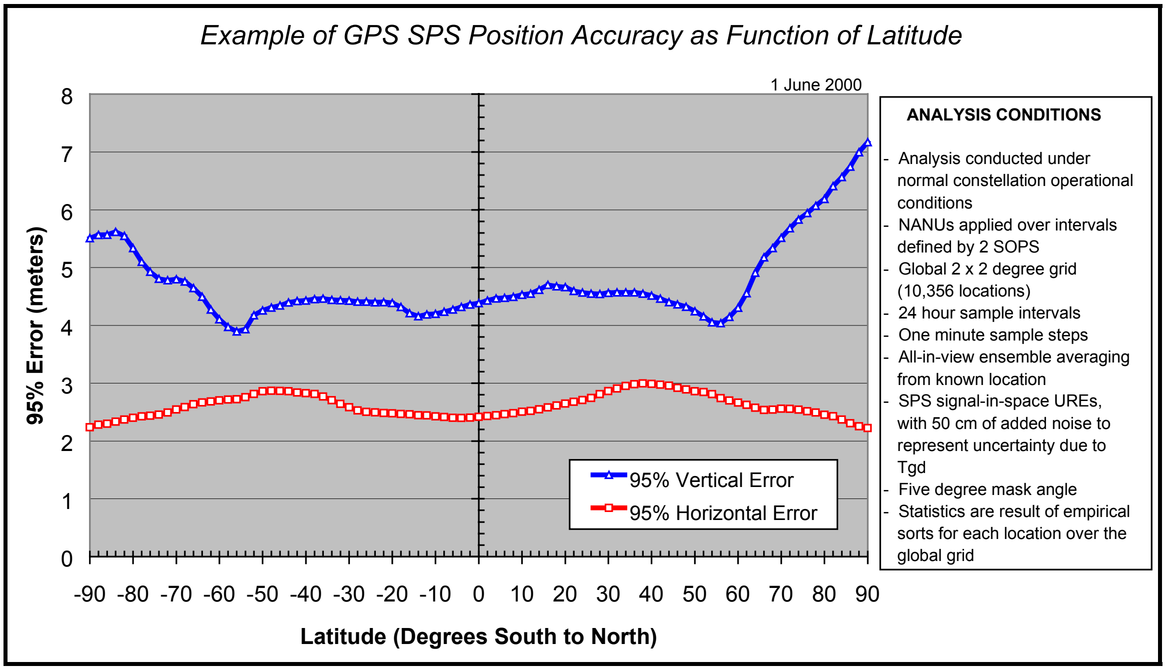


Figure A-5-1. Example of GPS SPS Position Accuracy as Function of Latitude

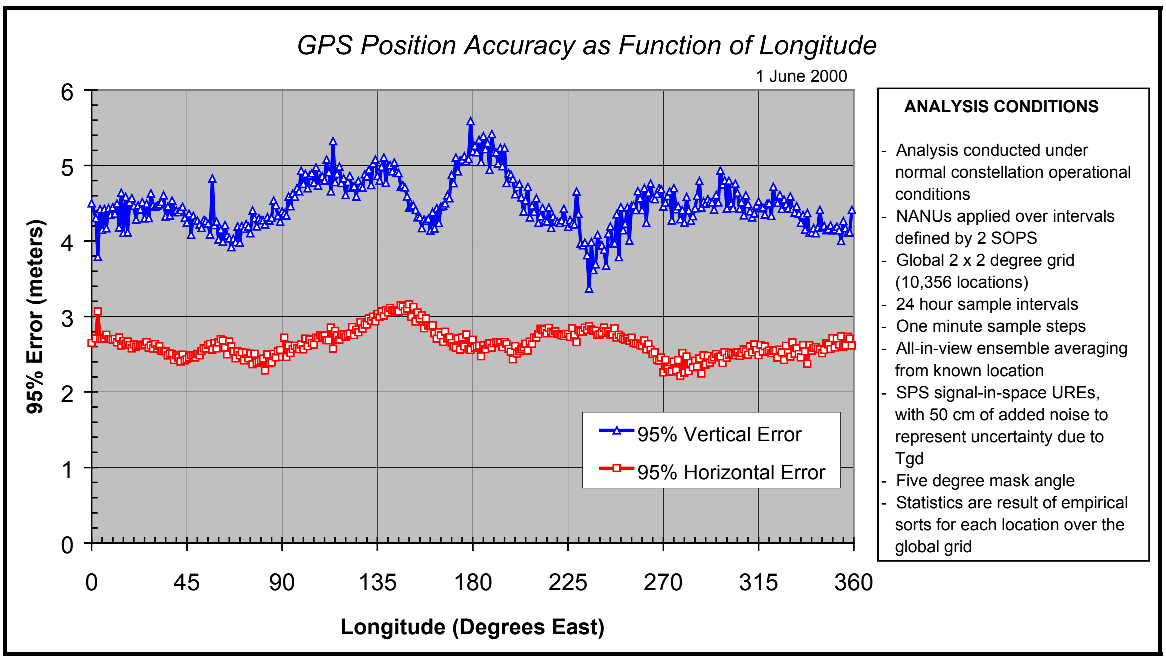


Figure A-5-2. Example of GPS SPS Position Accuracy as Function of Longitude

A-5.2 SPS SIS Accuracy Variation with Two Satellites Out

Global 95% accuracy for current operations does not change significantly as a function of two satellites being removed from service, as can be seen in Figure A-5-3 and Figure A-5-4. Worst-case site performance can vary considerably as would be expected, but is still well below the accuracy performance standard values.

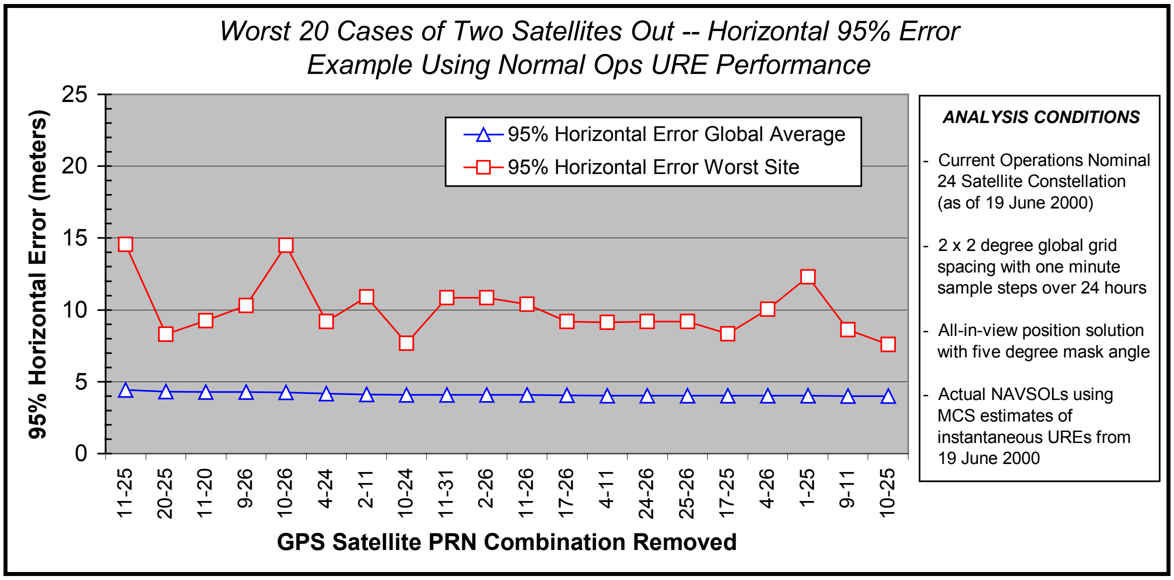


Figure A-5-3. Worst-Case Horizontal Performance with Two SVs Out, Current Ops URE

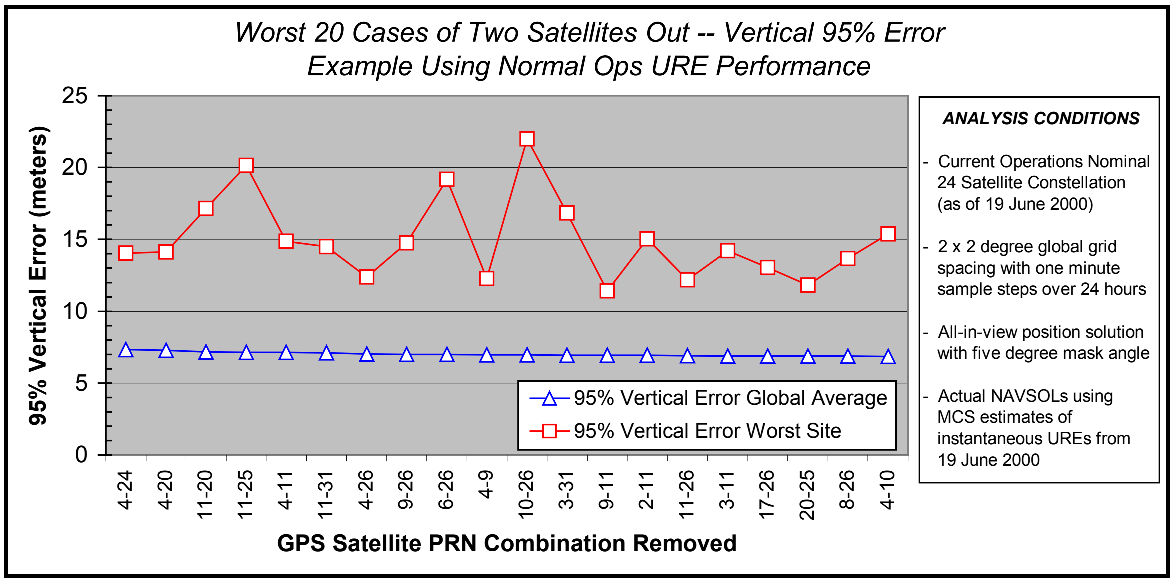


Figure A-5-4. Worst-Case Vertical Performance with Two SVs Out, Current Ops URE

Accuracy degrades considerably under the combination of worst-case satellite outages and worst-case URE performance, as shown in Figure A-5-5 and Figure A-5-6. Even under these conditions, all but one of the 276 two-satellite out cases supported the worst-case site horizontal accuracy standard, and all two-satellite out cases supported the vertical standard. Ensuring the accuracy standards are met when the system is operating at the outer edges of its operational limit will require close monitoring and management of system performance in the event the conditions that lead to worst-case performance are expected to occur.

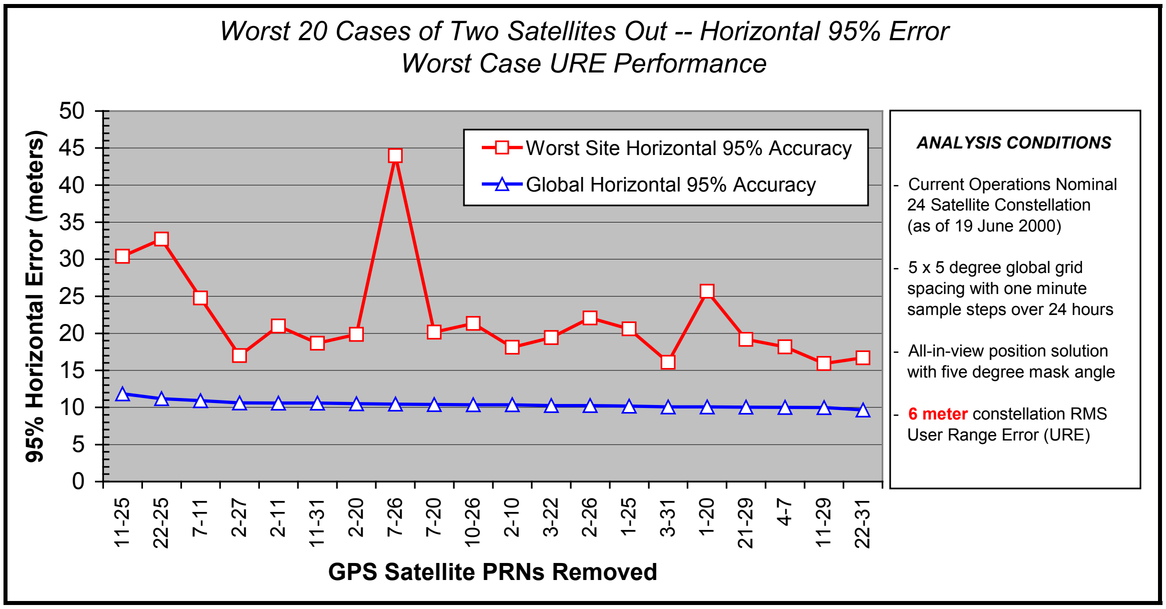


Figure A-5-5. Worst-Case Horizontal Performance with Two SVs Out, Worst-Case URE

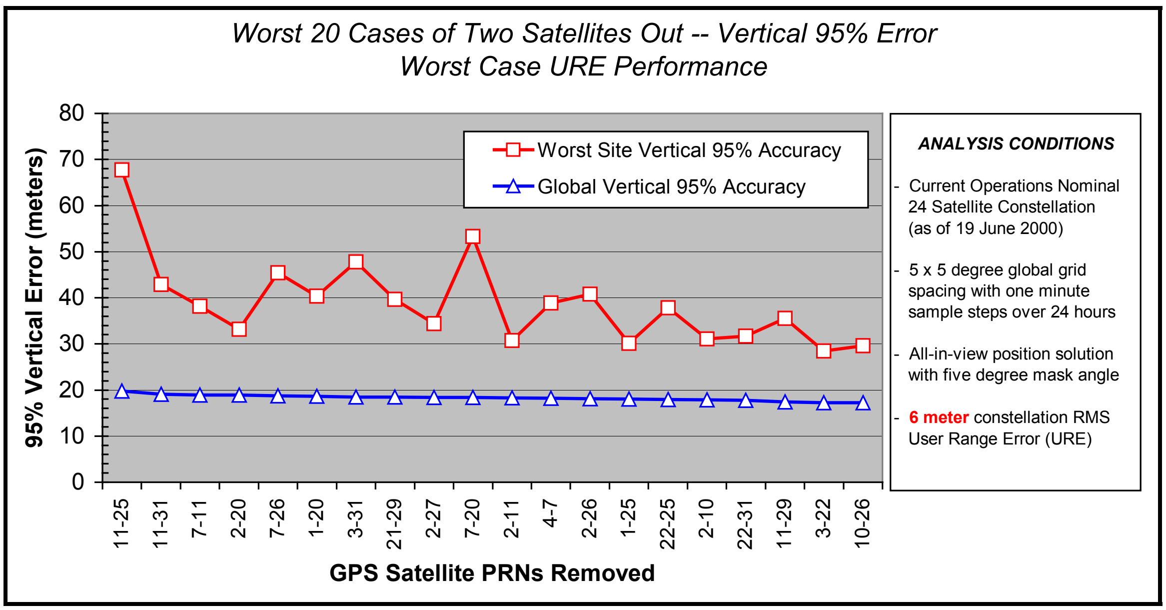


Figure A-5-6. Worst-Case Vertical Performance with Two SVs Out, Worst-Case URE

A-5.3 Representative SPS SIS Position Accuracy Characteristics

As seen in Figure A-2-3, the GPS constellation has historically enjoyed an overage of satellites above the core 24-satellite constellation number. This trend is illustrated best by viewing performance as seen over a representative month. Such a month of performance (June 2000) is shown in Figure A-5-7 and Figure A-5-8. As can be seen, both global average and worst-case site performance is generally very consistent.

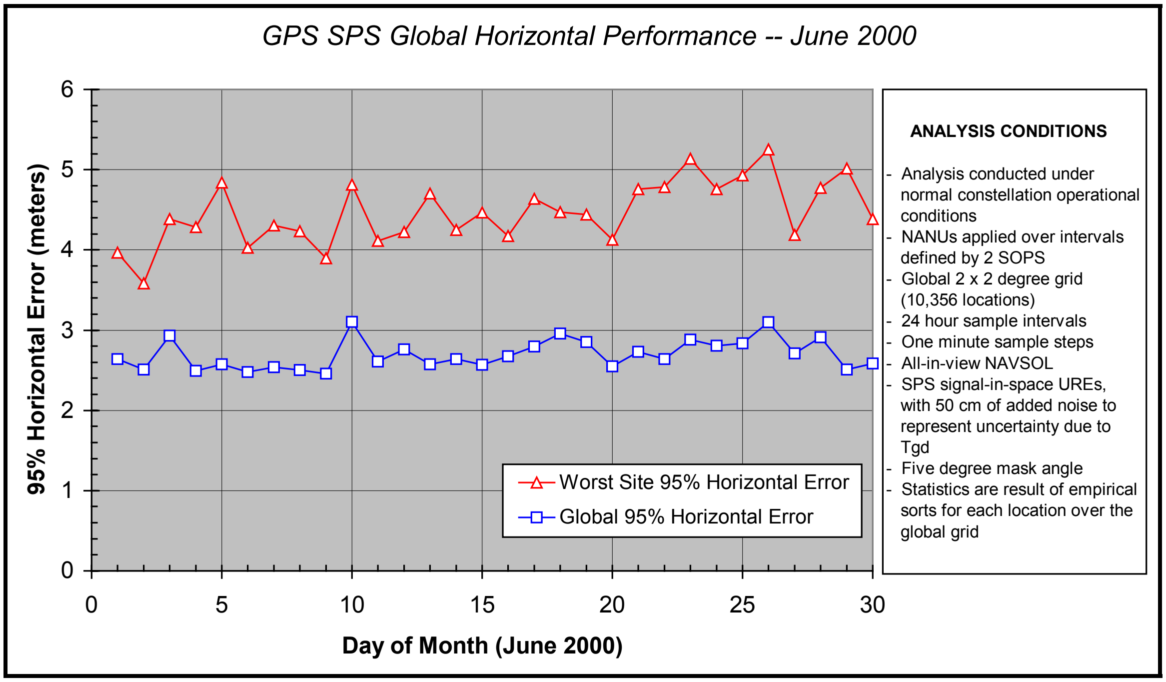


Figure A-5-7. Typical Example of GPS SPS SIS Horizontal Performance – June 2000

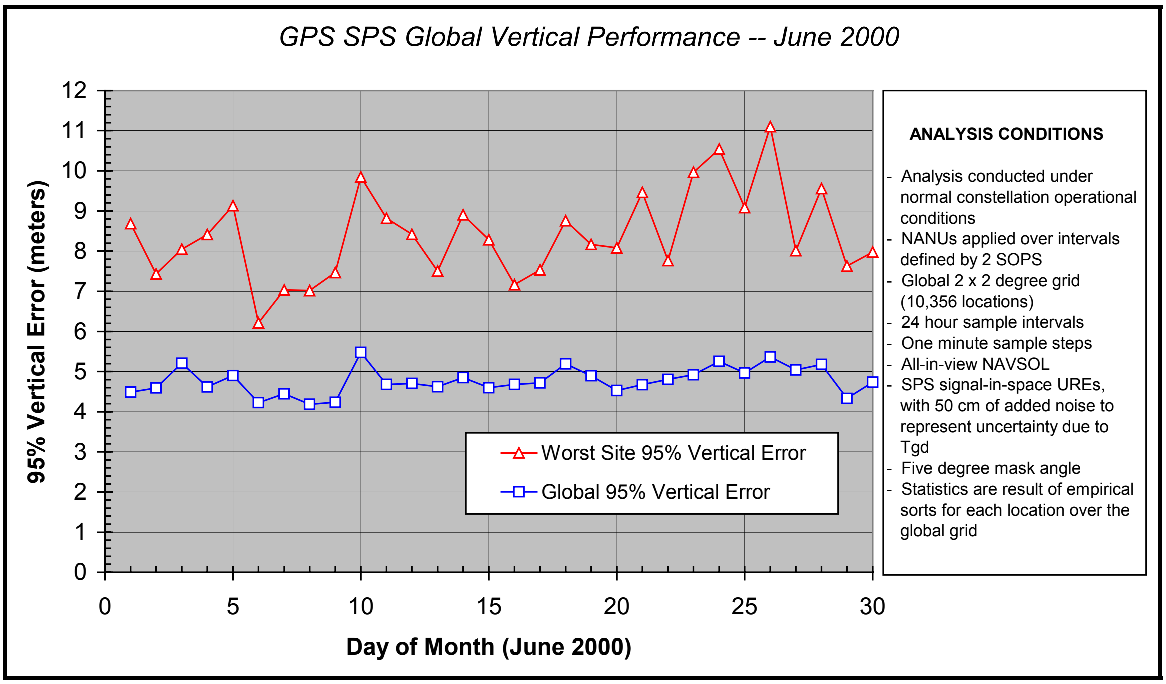


Figure A-5-8. Typical Example of GPS SPS SIS Vertical Performance – June 2000

A-5.4 SPS SIS Time Transfer Accuracy Characteristics

The SPS Performance Standard witnesses a transition to a different type of metric for SPS time transfer of UTC as defined by the United States Naval Observatory (USNO). The new metric is more in line with the basic stand-alone time transfer application, in that it assumes operations from a surveyed point and functions based upon an ensemble averaging of pseudo range residuals from all satellites in view. This metric removes performance variations due to geometry and leaves only those variations due to the statistical combination of UREs from all satellites in view over the sample interval. Figure A-5-9 illustrates the lack of time transfer performance impacts due to satellite removal. Figure A-5-10 shows a 30-day trend of time transfer performance, over the month of June 2000.

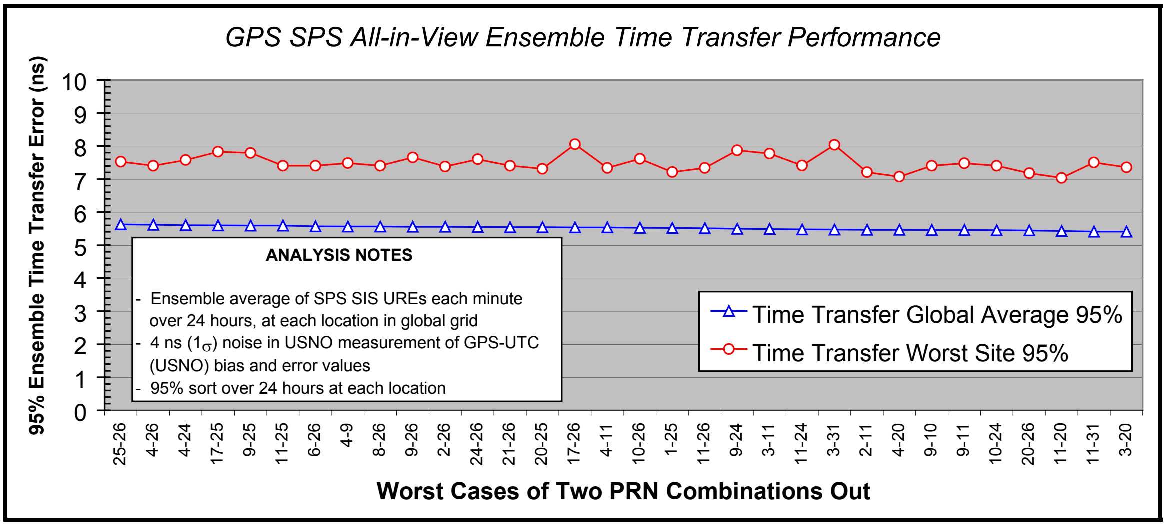


Figure A-5-9. GPS SPS Time Transfer Accuracy as Function of Two Satellites Removed

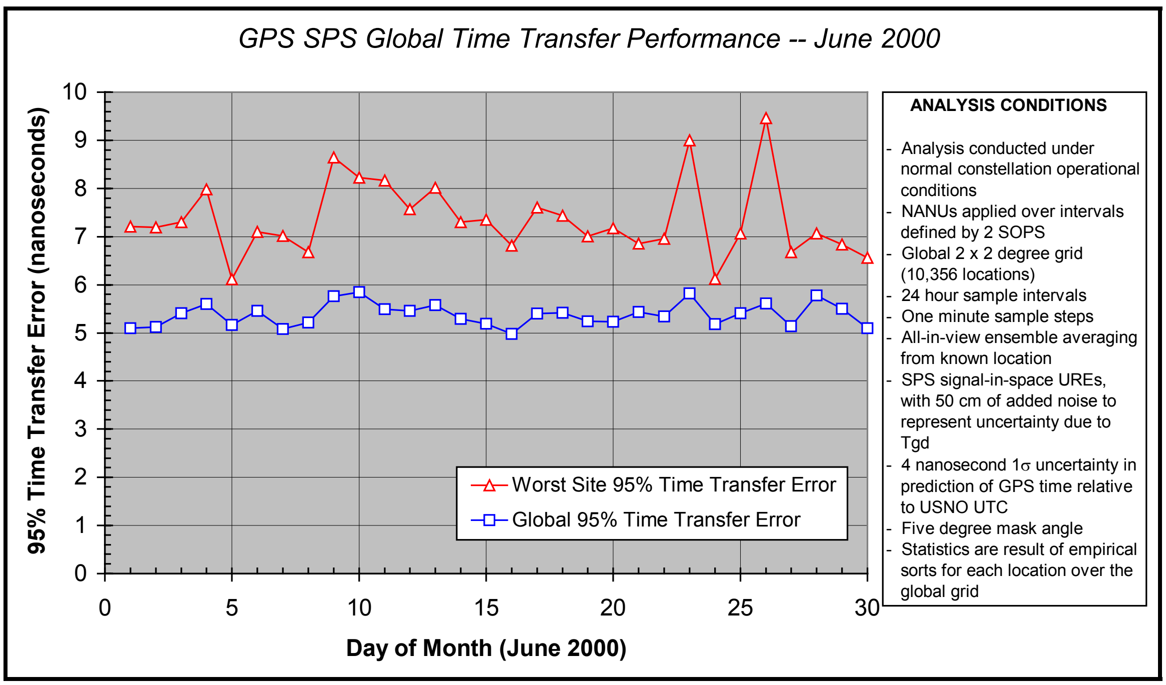


Figure A-5-10. Typical Example of GPS SPS SIS Time Transfer Performance – June 2000

A-5.5 A Description of Single-Frequency Receiver Performance

This section provides the civil community with estimates of single-frequency receiver performance that are representative of behavior during solar maximum. Single-frequency user performance is dominated by errors in the GPS single-frequency model representation of Total Electron Count (TEC) along the line-of-sight from the user to a GPS satellite. Errors in the GPS single-frequency model are primarily a function of solar flux density and its interactions with the Earth's magnetic field and upper atmosphere.

The information provided in this section was developed using PRISM model data supplied by the Air Force Research Laboratory (AFRL) and the Air Force Weather Agency (AFWA). PRISM combines electron density and other measurements with a sophisticated model of the upper atmosphere to generate a global estimate of electron density over a specified time interval. Electron densities are provided every 15 minutes at a 1° x 1° grid spacing, at 50 different altitudes ranging between 70 and 1,600 kilometers. This information was used, along with orbit and clock prediction error estimates, receiver noise and troposphere model error estimates, to generate instantaneous single-frequency UREs every minute over the selected 24-hour interval for all satellites in view, for 1,666 locations spread uniformly over the surface of the Earth. These system-level URE values were then used to generate and accumulate statistics on estimates of instantaneous single-frequency user position errors.

Solar flux density follows a trend established by the eleven-year solar cycle, at its peak as of this writing. Two days in June 2000 (3 and 8 June) were selected for assessment of typical single-frequency performance at solar maximum, as shown in Figure A-5-11. When evaluated against values trended since 1 January 1947, 3 and 8 June 2000 fall at the 61st and 66th percentiles respectively in magnitude of solar flux density. This information serves to provide a rough assessment of where the evaluated days fall in the range of historical density values.

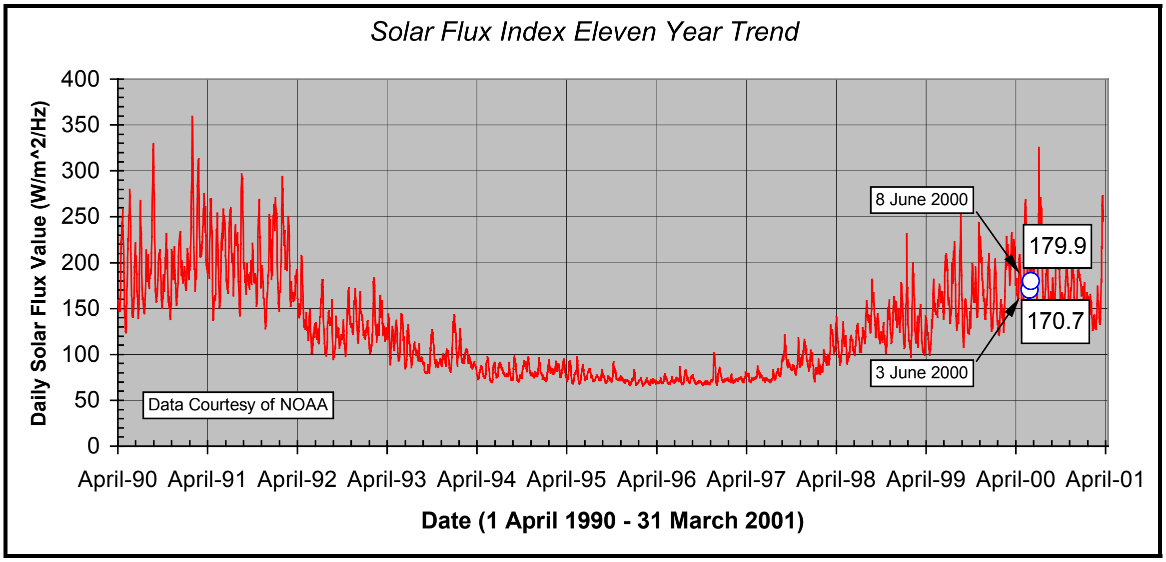


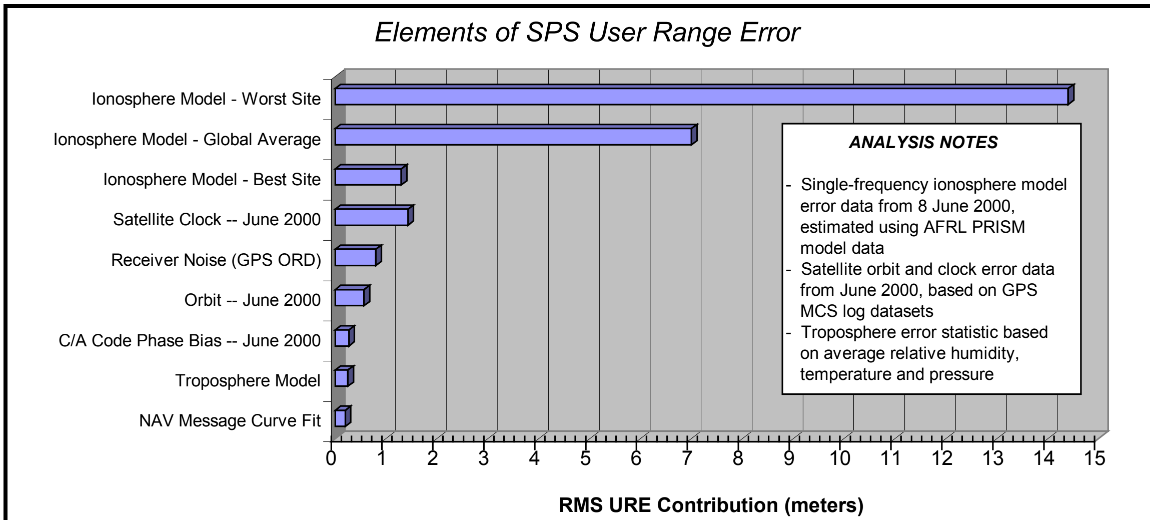
Figure A-5-11. Solar Flux Index Eleven Year Trend

Errors in the GPS single-frequency model presented in ICD-GPS-200C dominate single-frequency system URE performance. The contributions of the single-frequency model to URE are not however uniform, and in fact vary significantly on a global basis. Figure A-5-12 illustrates the range of error contributions to system URE made by the single-frequency model, and contrasts those contributions to the other elements that comprise the total URE.

As shown in Figure A-5-13, single-frequency system URE can vary greatly throughout the global service volume. Performance around the equator was significantly worse than that experienced at mid to high latitudes. Longitudinal variations were due primarily to the angular offset of the geographic and geomagnetic equators. RMS single-frequency system UREs were on average 4.3 times worse than dual-frequency system UREs on a global basis. RMS single-frequency system UREs at worst case sites were on the order of seven times or more worse than the corresponding dual-frequency system URE statistic.

SPS single-frequency positioning performance is necessarily affected by errors in the single-frequency model. The shaded areas in Figure A-5-14 show locations on 8 June 2000 where 95% horizontal performance was greater than 10 meters for all-in-view receivers, while Figure A-5-15 provides the same information for 95% vertical errors greater than 25 meters. Areas of increased error form bands about the geomagnetic equator. Figure A-5-16 indicates the cumulative distribution of 95% horizontal and vertical errors on a global basis. On 8 June 2000, 95% of the

Earth's surface experienced better than 16.4 meters horizontal (95%) performance, and better than 29 meters vertical (95%) performance. Similar results were found on 3 June 2000.



	NAV Message Curve Fit	Troposphere Model	C/A Code Phase Bias -- June 2000	Orbit -- June 2000	Receiver Noise (GPS ORD)	Satellite Clock -- June 2000	Ionosphere Model - Best Site	Ionosphere Model - Global Average	Ionosphere Model - Worst Site
RMS Contribution to URE (m)	0.20	0.25	0.27	0.57	0.80	1.43	1.30	7.00	14.40

Figure A-5-12. Elements of SPS User Range Error

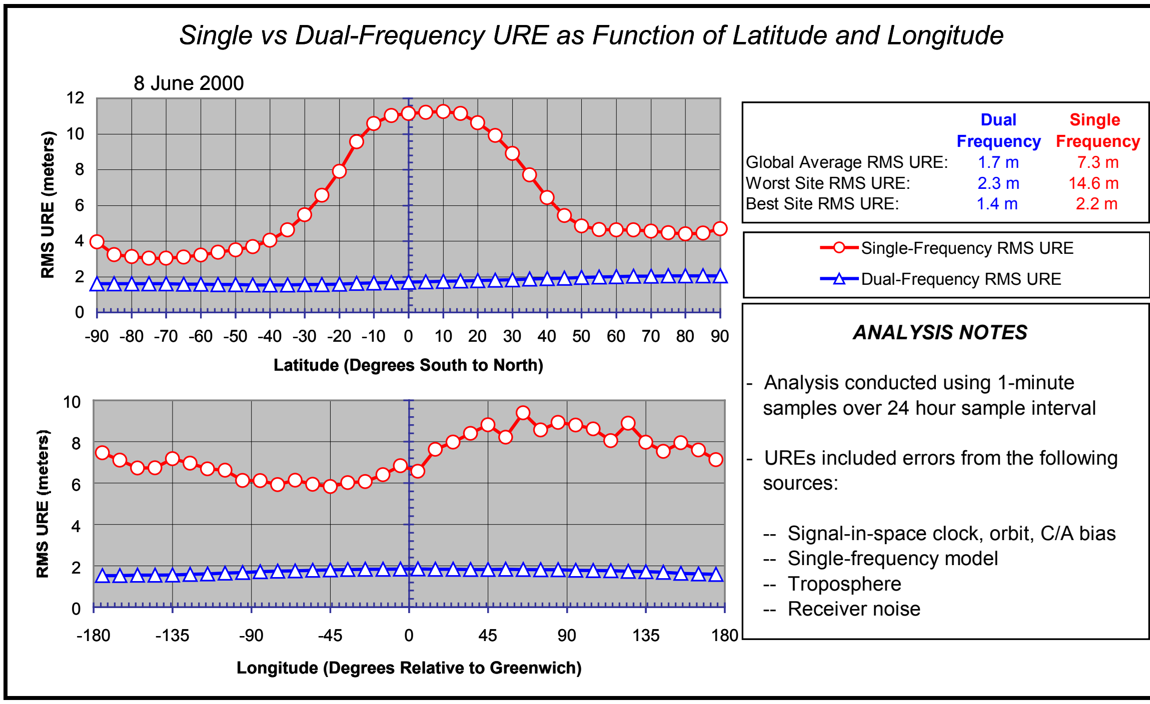


Figure A-5-13. Dual versus Single-Frequency URE Behavior

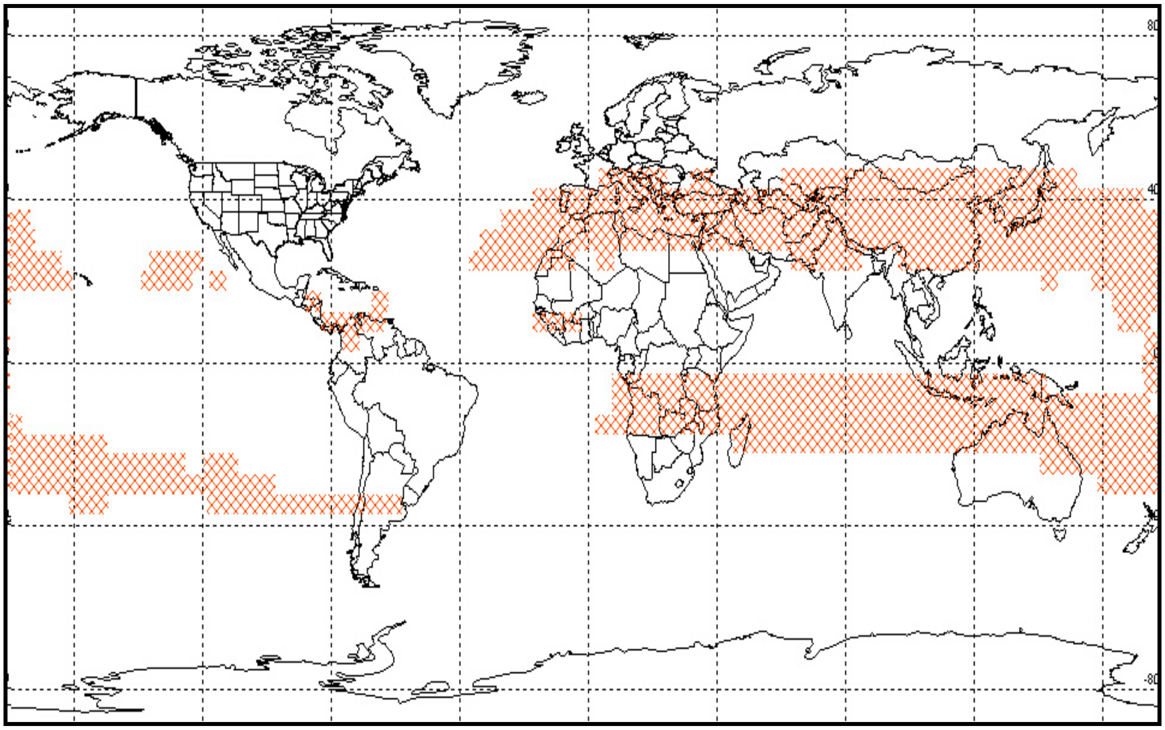


Figure A-5-14. Single-Frequency 95% Horizontal Errors over 10 meters – 8 June 2000

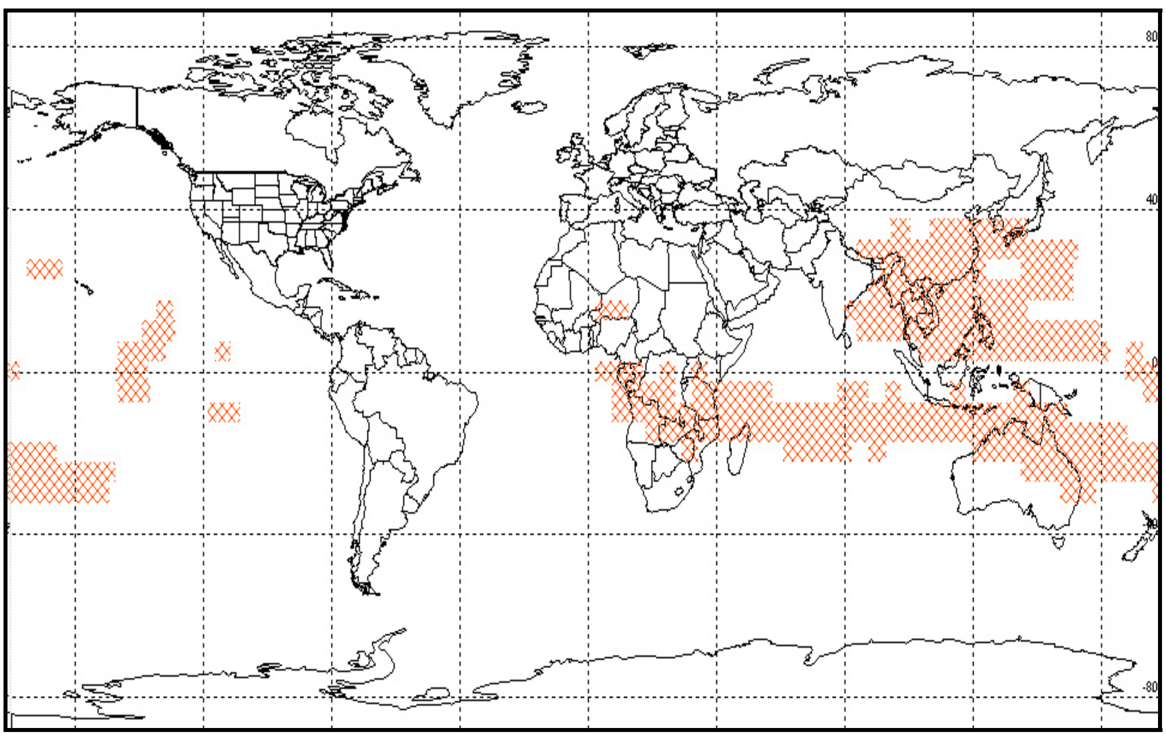


Figure A-5-15. Single-Frequency 95% Vertical Errors over 25 meters – 8 June 2000

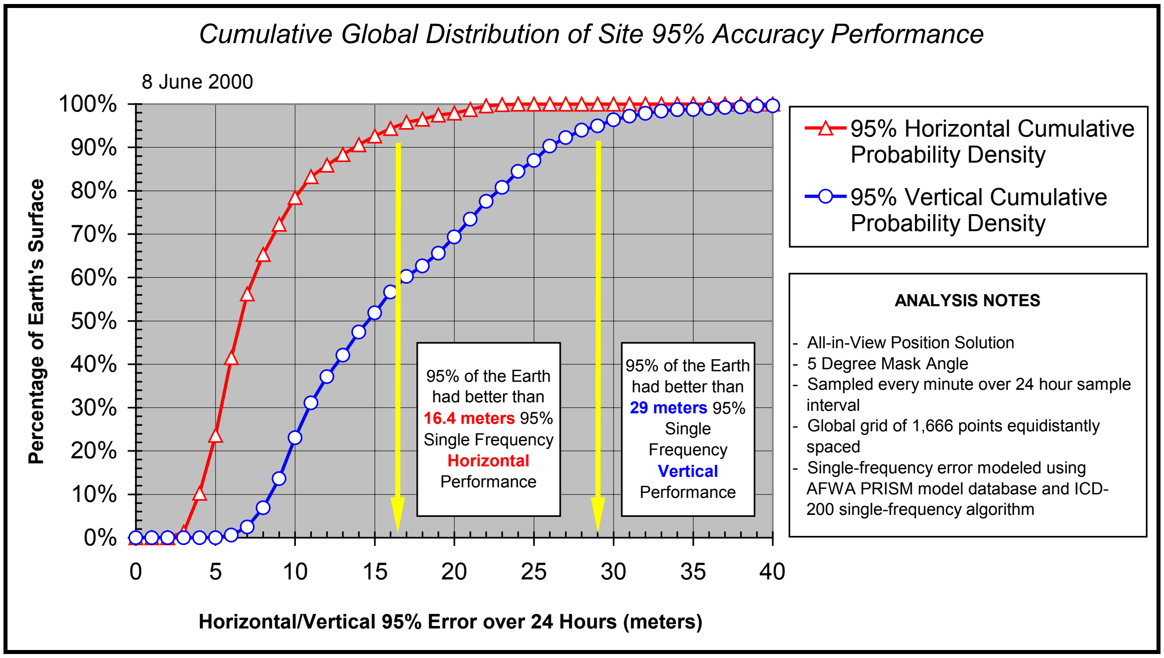


Figure A-5-16. Cumulative Global Distribution of Site 95% Accuracy Performance

In the absence of relatively stronger concentrations of electrons found around the geomagnetic equator, middle (geomagnetic) latitude performance is affected most significantly by disturbances in the Earth's magnetic field. Accuracy is not normally significantly affected at higher latitudes. The primary concern at higher latitudes is impacts to service availability, due to the possibility of scintillation brought on by an influx of energetic solar particles.

Examples of individual site horizontal and vertical performance impacts due to single-frequency model errors are provided in Figure A-5-17 and Figure A-5-18. These figures illustrate single-frequency user performance at the worst-case site anywhere in the service volume on 8 June 2000.

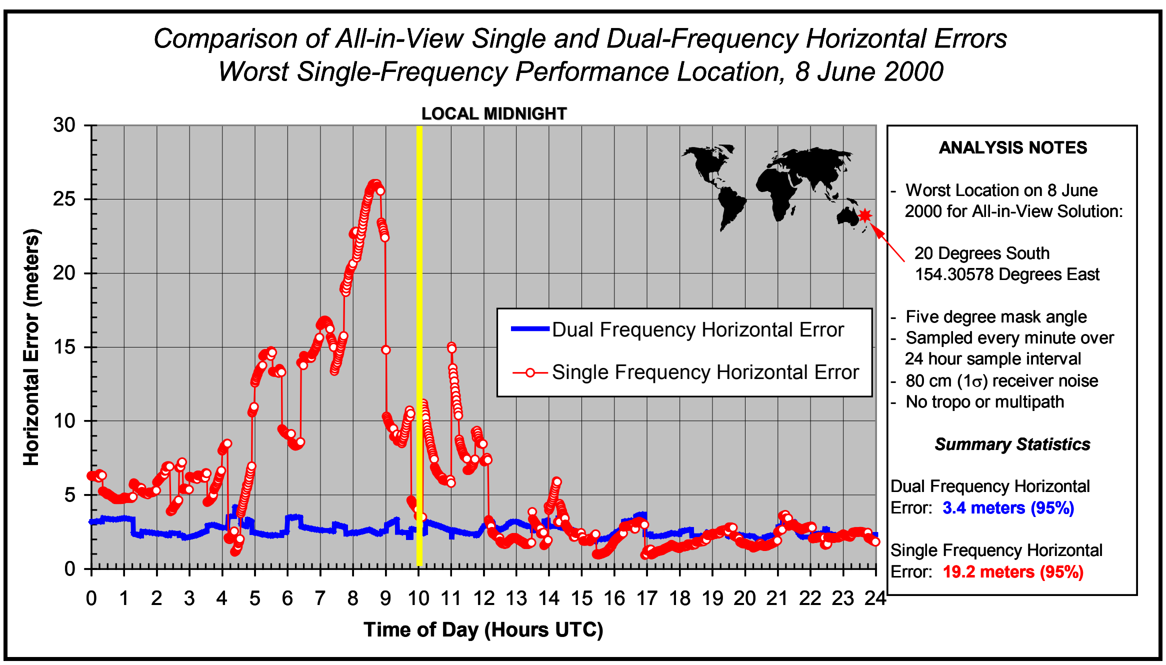


Figure A-5-17. Example Worst Site Single-Frequency Horizontal Performance

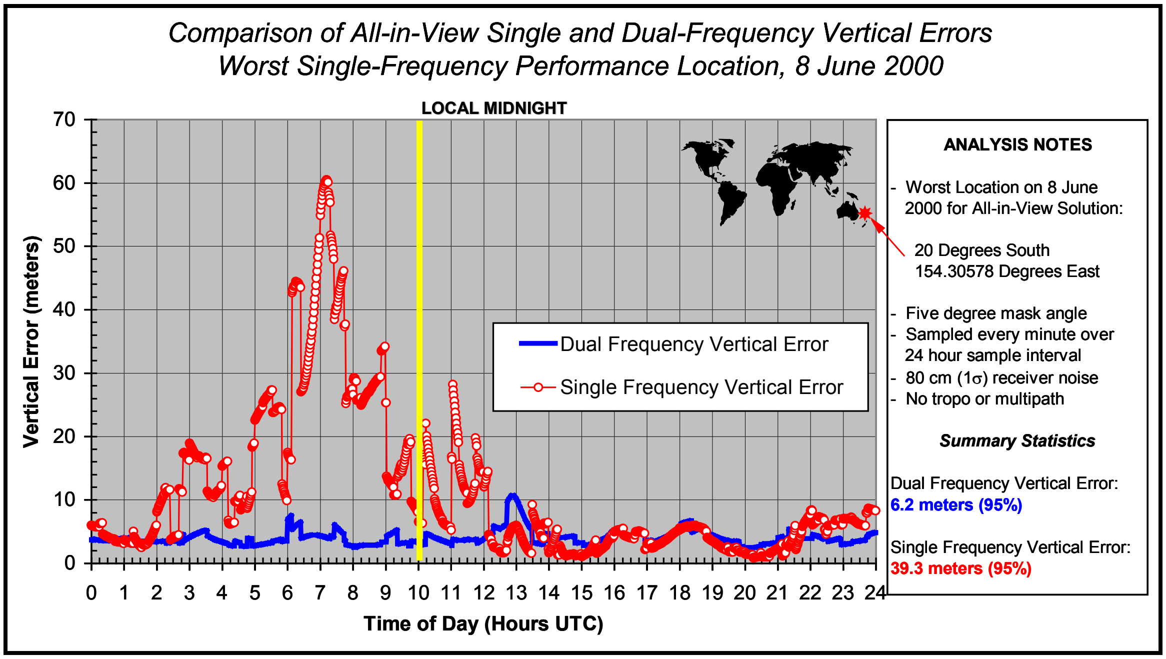


Figure A-5-18. Example Worst Site Single-Frequency Vertical Performance

The most significant features of the error plots to note are the significant jumps in error approximately five hours before local midnight, and fact that horizontal error jumped along with vertical error. Horizontal error increases occurred in concert with the rapid appearance of a gradient in electron density over the region associated with the worst-case location.

In general, position solution errors increase not necessarily due to increases in electron density, but to gradients in the electron density above a given location that causes wide variations in single-frequency delay for all satellites used in the position solution. The other effect of gradients in electron density is to change significantly the distribution characteristics of GPS errors.

In a two-frequency position solution, RMS vertical errors are generally about 50% larger than RMS horizontal errors below a latitude of 55°, and two to three times larger at the poles. For single-frequency position solutions, RMS vertical errors can be over six times worse than RMS horizontal errors within 20° of the geomagnetic equator.

Due to the effect of electron density gradients, the ratio of east and north errors for the single-frequency position solution in an East-North-Up (ENU) coordinate system can also be impacted. In a dual-frequency position solution, RMS east and RMS north errors are approximately equivalent at the equator and the poles, and RMS east errors are generally 20% smaller than RMS north errors at mid-latitudes. For a single-frequency solution, RMS east errors can be 50% smaller than RMS north errors within 20° of the geomagnetic equator, but several times larger at higher latitudes.

Table A-5-1 through Table A-5-4 present summary statistic estimates for single versus dual-frequency all-in-view receivers across the globe on 3 and 8 June 2000.

Table A-5-1. GPS Single-Frequency All-in-View User Performance Summary, 3 June 2000

	Vertical Error Statistics		Horizontal Error Statistics	
	50%	95%	50%	95%
Global Average	5.8 meters	16.8 meters	3.1 meters	8.3 meters
Worst Site	14.0 meters	44.0 meters	7.7 meters	19.7 meters

Table A-5-2. GPS Dual-Frequency All-in-View User Performance Summary, 3 June 2000

	Vertical Error Statistics		Horizontal Error Statistics	
	50%	95%	50%	95%
Global Average	2.1 meters	5.6 meters	1.6 meters	3.1 meters
Worst Site	3.3 meters	9.2 meters	2.1 meters	5.0 meters

Table A-5-3. GPS Single-Frequency All-in-View User Performance Summary, 8 June 2000

	Vertical Error Statistics		Horizontal Error Statistics	
	50%	95%	50%	95%
Global Average	5.5 meters	16.2 meters	2.9 meters	7.8 meters
Worst Site	14.4 meters	39.3 meters	7.2 meters	19.2 meters

Table A-5-4. GPS Dual-Frequency All-in-View User Performance Summary, 8 June 2000

	Vertical Error Statistics		Horizontal Error Statistics	
	50%	95%	50%	95%
Global Average	1.8 meters	4.3 meters	1.3 meters	2.6 meters
Worst Site	2.5 meters	7.1 meters	1.9 meters	4.2 meters

The most significant aspect of performance affected by single-frequency model error is time transfer. Figure A-5-19 provides an example of time transfer performance at the worst-case location from a position solution error perspective. Table A-5-5 presents a summary of single versus dual-frequency ensemble time transfer performance on 3 and 8 June 2000.

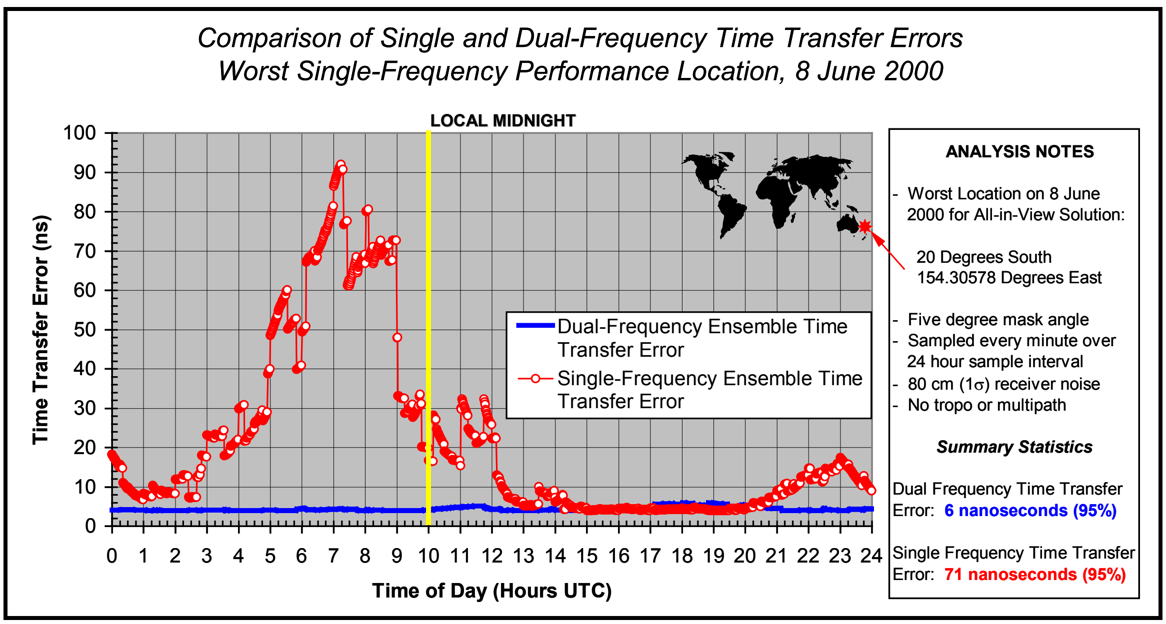


Figure A-5-19. Example Worst Site Single-Frequency Time Transfer Performance

Table A-5-5. GPS End-User Ensemble Time Transfer Performance Summary

	Dual-Frequency 95%		Single-Frequency 95%	
	3 June 2000	8 June 2000	3 June 2000	8 June 2000
Global Average	6 nanoseconds	5 nanoseconds	46 nanoseconds	35 nanoseconds
Worst Site	7 nanoseconds	7 nanoseconds	119 nanoseconds	86 nanoseconds
Best Site	4 nanoseconds	4 nanoseconds	7 nanoseconds	6 nanoseconds

As discussed extensively throughout this document, SPS performance standards include only those factors under the control of the U.S Government. Accuracy standards were established with the worst two satellites removed, and with a six-meter constellation RMS SIS URE. For comparison purposes, Table A-5-6 contrasts the SIS position accuracy standard established in Section 3.3 against a conservative estimate of end-user performance for a user equipped with a representative receiver. The environmental and receiver error contributions included in the single-frequency end user performance estimates in Table A-5-6 are as follows:

- Single-frequency ionosphere propagation model error: 7 meters (1σ)
- Troposphere propagation model error: 25 centimeters (1σ)
- Receiver thermal noise: 80 centimeters (1σ)

Table A-5-6. Comparison of SIS Performance Standards and End-User Performance

SPS Position Accuracy Parameter	SIS Position Accuracy Standard (Section 3.3, Table 3-6)	Single-Frequency User Performance Given Accuracy Standard Conditions
Global 95% Horizontal Error	13 meters	33 meters
Global 95% Vertical Error	22 meters	73 meters

A-5.6 Range Rate and Range Acceleration Error Behavior After SA

Previous documents established standards for range rate error and range acceleration error as follows:

- Range Rate Error: 2 meters/second Not-to-Exceed (NTE)
- Range Acceleration Error:
  - ✓ 8 millimeters/second^2 95%
  - ✓ 19 millimeters/second^2 NTE

These standards were established specifically as a bound on SA contributions to civil differential systems. With the removal of SA, the behavior of range rate and range acceleration error has changed considerably. Representative examples of current performance for these metrics are presented in Figure A-5-20 and Figure A-5-21.

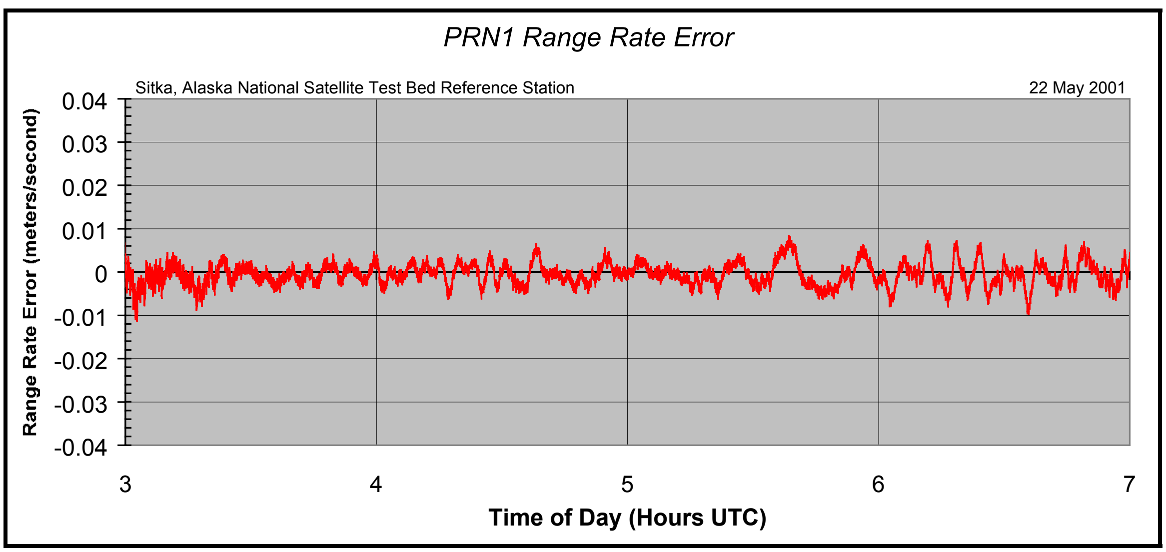


Figure A-5-20. Representative Example of Current Measured Range Rate Error

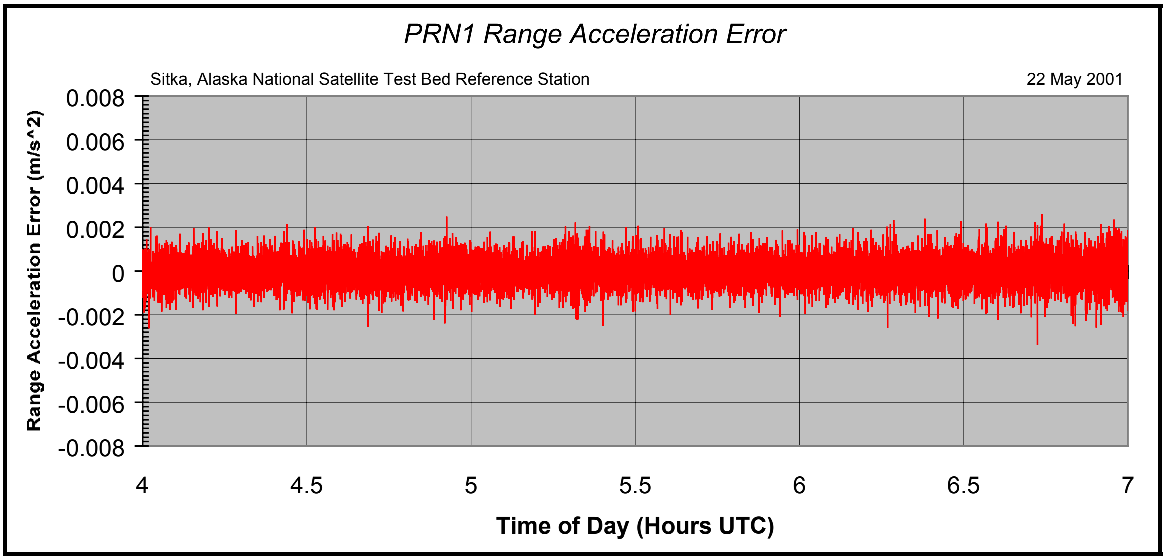


Figure A-5-21. Representative Example of Current Measured Range Acceleration Error

High frequency noise characteristics seen in the above figures are indicative of noise inherent in the measurement process, These noise characteristics are due almost entirely to receiver thermal noise in the tracking loops, although a small amount is contributed by the short-term stability of the L1 frequency source on-board the satellite. For the receiver used to track the above measurements, range rate error was typically below one centimeter/second Root Mean Square (RMS), while range acceleration error was typically below two millimeters/second^2 RMS.

Low frequency noise characteristics are not readily visible in a plot, since they are driven by slowly changing errors in measured navigation signal Doppler. Doppler errors are driven by predicted state errors in the transmitted satellite velocity vector, and the slow drift of the on-board satellite frequency standard. The best indicator of steady state range rate error due to predicted satellite ephemeris and clock states is the rate-of-change of SIS UREs. Typically, the range rate error associated with steady state SIS UREs is less than one millimeter/second RMS.

APPENDIX B

Key Terms, Definitions, and Acronyms

SECTION B-1 Key Terms and Definitions

Almanac Longitude of the Ascending Node (Ω_o): Equatorial angle from the Prime Meridian (Greenwich) at the weekly epoch to the ascending node at the ephemeris reference epoch.

Coarse/Acquisition (C/A) Code: A PRN code sequence used to modulate the GPS L1 carrier.

Corrected Longitude of the Ascending Node (Ω_k) and Geographic Longitude of the Ascending Node (GLAN): Equatorial angle from the Prime Meridian (Greenwich) to the ascending node, both at arbitrary time t_k.

Dilution of Precision (DOP): The magnifying effect on GPS position error induced by mapping GPS ranging errors into position within the specified coordinate system through the geometry of the position solution. The DOP varies as a function of satellite positions relative to user position. 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.

Equatorial Angle: An angle along the equator in the direction of Earth rotation.

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

Groundtrack Equatorial Crossing (GEC, λ, 2 SOPS GLAN): Equatorial angle from the Prime Meridian (Greenwich) to the location a groundtrack intersects the equator when crossing from the Southern to the Northern hemisphere. GEC is equal to Ω_k when the argument of latitude (Φ) is zero.

Instantaneous User Range Error (URE): The difference between the pseudo range measured at a given location and the expected pseudo range, as derived from the navigation message and the true user position, neglecting the bias in receiver clock relative to GPS time. A signal-in-space (SIS) URE includes residual orbit, satellite clock, and group delay errors. A system URE (sometimes known as a User Equivalent Range Error, or UERE) contains all line-of-sight error sources, to include SIS, single-frequency ionosphere model error, troposphere model error, multipath and receiver noise.

Longitude of Ascending Node (LAN): A general term for the location of the ascending node – the point that an orbit intersects the equator when crossing from the Southern to the Northern hemisphere.

Longitude of the Groundtrack Equatorial Crossing (GEC, λ, 2 SOPS GLAN): Equatorial angle from the Prime Meridian (Greenwich) to the location a groundtrack intersects the equator when crossing from the Southern to the Northern hemisphere. GEC is equal to Ω_k when the argument of latitude (Φ) is zero.

Mean Down Time (MDT): A measure of time required to restore function after any downing event.

Mean Time Between Downing Events (MTBDE): A measure of time between any downing events.

Mean Time Between Failures (MTBF): A measure of time between unscheduled downing events.

Mean Time to Restore (MTTR): A measure of time required to restore function after an unscheduled downing event.

Navigation Message: Data contained in each satellite's ranging signal and consisting of 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. The message structure is described in Section 2.1.2 of the SPS Performance Standard.

Operational Satellite: A GPS satellite which is capable of, but is not necessarily transmitting a usable ranging signal.

PDOP Availability: Defined to be the percentage of time over any 24-hour interval that the PDOP value is less than or equal to its threshold for any point within the service volume.

Positioning Accuracy: Defined to be the statistical difference, at a 95% probability, between position measurements and a surveyed benchmark for any point within the service volume over any 24-hour interval.

- **Horizontal Positioning Accuracy:** Defined to be the statistical difference, at a 95% probability, between horizontal position measurements and a surveyed benchmark for any point within the service volume over any 24-hour interval.
- **Vertical Positioning Accuracy:** Defined to be the statistical difference, at a 95% probability, between vertical position measurements and a surveyed benchmark for any point within the service volume over any 24-hour interval.

Position Solution: An estimate of a user's location derived from ranging signal measurements and navigation data from GPS.

Position Solution Geometry: The set of direction cosines that define the instantaneous relationship of each satellite's ranging signal vector to each of the position solution coordinate axes. See DILUTION OF PRECISION.

Pseudo Random Noise (PRN): A binary sequence that appears to be random over a specified time interval unless the shift register configuration and initial conditions for generating the sequence are known. Each satellite generates a unique PRN sequence that is effectively uncorrelated (orthogonal) to any other satellite's code over the integration time constant of a receiver's code tracking loop.

Representative SPS Receiver: The minimum signal reception and processing assumptions employed by the U.S. Government to characterize SPS performance in accordance with performance standards defined in Section 3 of the SPS Performance Standard. Representative SPS receiver capability assumptions are identified in Section 2.2 of the SPS Performance Standard.

Right Ascension of Ascending Node (RAAN): Equatorial angle from the celestial principal direction to the ascending node.

Root Mean Square (RMS) SIS URE: A statistic that represents instantaneous SIS URE performance in an RMS sense over some sample interval. The statistic can be for an individual satellite or for the entire constellation. The sample interval for URE assessment used in the SPS Performance Standard is 24 hours.

Selective Availability: Protection technique formerly employed to deny full system accuracy to unauthorized users. SA was discontinued effective midnight May 1, 2000.

Service Availability: Defined to be the percentage of time over any 24-hour interval that the predicted 95% positioning error is less than its threshold for any given point within the service volume.

- **Horizontal Service Availability:** Defined to be the percentage of time over any 24-hour interval that the predicted 95% horizontal error is less than its threshold for any point within the service volume.
- **Vertical Service Availability:** Defined to be the percentage of time over any 24-hour interval that the predicted 95% vertical error is less than its threshold for any point within the service volume.

Service Degradation: a condition over a time interval during which one or more SPS performance standards are not supported.

Service Failure: A condition over a time interval during which a healthy GPS satellite's ranging signal exceeds the Not-to-Exceed (NTE) SPS SIS URE tolerance.

Service Reliability: The percentage of time over a specified time interval that the instantaneous SIS SPS URE is maintained within a specified reliability threshold at any given point within the service volume, for all healthy GPS satellites.

Service Volume: The spatial volume supported by SPS performance standards. Specifically, the SPS Performance Standard supports the terrestrial service volume. The terrestrial service volume covers from the surface of the Earth up to an altitude of 3,000 kilometers.

SPS Performance Envelope: The range of nominal variation in specified aspects of SPS performance.

SPS Performance Standard: A quantifiable minimum level for a specified aspect of GPS SPS performance. SPS performance standards are defined in Section 3.0.

SPS Ranging Signal: An electromagnetic signal originating from an operational satellite. The SPS ranging signal consists of a Pseudo Random Noise (PRN) C/A code, a timing reference and sufficient data to support the position solution generation process. A description of the GPS SPS signal is provided in Section 2. The formal definition of the SPS ranging signal is provided in ICD-GPS-200C.

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

SPS SIS User Range Error (URE) Statistic:

- A satellite SPS SIS URE statistic is defined to be the Root Mean Square (RMS) difference between SPS ranging signal measurements (neglecting user clock bias and errors due to propagation environment and receiver), and "true" ranges between the satellite and an SPS user at any point within the service volume over a specified time interval.
- A constellation SPS SIS URE statistic is defined to be the average of all satellite SPS SIS URE statistics over a specified time interval.

Steady-State Behavior: Behavior within statistical expectations.

Time Transfer Accuracy Relative to UTC (USNO): The difference at a 95% probability between user UTC time estimates and UTC (USNO) at any point within the service volume over any 24-hour interval.

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

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

User Navigation Error (UNE): Given a sufficiently stationary and ergodic satellite constellation ranging error behavior over a minimum sample interval, 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 assumptions will cause the UNE to diverge from a RMS value based on actual measurements.

User Range Accuracy (URA): A conservative representation of each satellite's expected (1σ) SIS URE performance (excluding residual group delay) based on historical data. A URA value is provided that is representative over the curve fit interval of the navigation data from which the URA is read. The URA is a coarse representation of the URE statistic in that it is quantized to the levels represented in ICD-GPS-200C.

SECTION B-2 Acronyms

BIPM	International Bureau of Weights and Measures
bps	bits per second
BPSK	Bipolar-Phase Shift Key
C/A	Coarse/Acquisition
C/N_o	Signal-to-Noise Ratio
CS	Control Segment
dBi	Decibels, isotropic
dBW	Decibels, watt
DoD	Department of Defense
DOP	Dilution of Precision
DOT	Department of Transportation
ECEF	Earth-Centered, Earth-Fixed
ERD	Estimated Range Deviation
FAA	Federal Aviation Administration
FOC	Full Operational Capability
FRP	Federal Radionavigation Plan
GEC	Groundtrack Equatorial Crossing
GPS	Global Positioning System
GLAN	Geographic Longitude of the Ascending Node
GA	Ground Antenna
HDOP	Horizontal Dilution of Precision
HMI	Hazardously Misleading Information
HOW	Hand-Over Word
HUNE	Horizontal Component of the User Navigation Error
ICD	Interface Control Document
ID	Identification
IGEB	Interagency GPS Executive Board
IOC	Initial Operational Capability
IODC	Issue of Data, Clock
IODE	Issue of Data, Ephemeris
ION	Institute of Navigation
JPL	Jet Propulsion Laboratory
JPO	Joint Program Office
LAN	Longitude of the Ascending Node
LBMON	L-Band Monitor computer program
LSB	Least Significant Bit
LSF	Leap Seconds Future
Mbps	Million bits per second
MCS	Master Control Station
MDT	Mean Down Time
MHz	Megahertz
MOA	Memorandum of Agreement

MS	Monitor Station
MSB	Most Significant Bit
MTBDE	Mean Time Between Downing Events
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NANU	Notice: Advisory to Navigation Users
NASA	National Aeronautics and Space Administration
NAVSOL	Navigation Solution
NOTAM	Notice to Airmen
NSC	Non-Standard C/A-Code
NTE	Not-To-Exceed
OCS	Operational Control System
ORD	Observed Range Deviation
PDD	Presidential Decision Directive
PDOP	Position Dilution of Precision
PPS	Precise Positioning Service
PRN	Pseudo Random Noise
PUNE	3 Dimensional Position Component of the User Navigation Error
P(Y)	Precise or (Y) code
RAAN	Right Ascension of the Ascending Node
RF	Radio Frequency
RHCP	Right Hand Circularly Polarized
RMA	Reliability, Maintainability, Availability
RMS	Root Mean Square
SA	Selective Availability
SIS	Signal-in-Space
SPS	Standard Positioning Service
SS	Space Segment
SV	Space Vehicle (short hand notation for a GPS satellite)
TDOP	Time Dilution of Precision
TEC	Total Electron Count
T_{GD}	Estimated Group Delay Differential
TLM	Telemetry
TOW	Time of Week
TT&C	Telemetry, Tracking, and Commanding
TUNE	Time Component of the User Navigation Error
UE	User Equipment
UERE	User Equivalent Range Error
UNE	User Navigation Error
URA	User Range Accuracy
URE	User Range Error
U.S.	United States
USNO	U.S. Naval Observatory
UTC (USNO)	Coordinated Universal Time as represented by the United States Naval Observatory
VDOP	Vertical Dilution of Precision
VUNE	Vertical Component of the User Navigation Error
WGS 84	World Geodetic System 1984