



An Analysis of Global Positioning System Standard Positioning Service Performance for 2024

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Executive Summary

Applied Research Laboratories, The University of Texas at Austin (ARL:UT) examined the performance of the Global Positioning System (GPS) throughout 2024 for the U.S. Space Force (USSF) Space Systems Command (SSC), Military Communications & Positioning, Navigation, and Timing (PNT) Program Executive Office (PEO).

This report is based upon work supported by SSC through U.S. Navy Naval Sea Systems Command (NAVSEA) Contract N00024-17-D-6421, Task Order 5101070, “GNSS Signal Performance and Anomaly Analysis.”

Performance is defined by the 2020 Standard Positioning Service (SPS) Performance Standard (SPS PS 2020) [1]. The performance standard provides the U.S. government’s assertions regarding the expected performance of GPS. This report covers those assertions which can be verified by anyone with knowledge of standard GPS data analysis practices, familiarity with the relevant signal specification, and access to a GPS data archive. The few assertions that are not covered are noted in the summary and the reasons are discussed in the text.

The assertions evaluated include those of coverage, accuracy, integrity, continuity, and availability of the GPS signal-in-space (SIS) along with the assertions on accuracy of positioning and time transfer. Chapter 1 is an introduction to the report. Chapter 2 contains a tabular summary of performance stated in terms of the metrics provided in the SPS PS 2020. Chapter 3 presents a more detailed explanation of the analysis conducted in evaluating each assertion. The assertions are presented in order of appearance in the SPS PS.

All of the LNAV SPS PS 2020 assertions examined in this report were met in 2024. All of the CNAV SPS PS 2020 assertions except two examined in this report were met in 2024. The exceptions were the integrity and P_{sat} assertions. For more information, see Section 3.3.1 and Section 3.3.3.

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Chapter 1

Introduction

Applied Research Laboratories, The University of Texas at Austin (ARL:UT) examined the performance of the Global Positioning System (GPS) throughout 2024 for the U.S. Space Force (USSF) Space Systems Command (SSC), Military Communications & Positioning, Navigation, and Timing (PNT) Program Executive Office (PEO). This report is based upon work supported by SSC through U.S. Navy Naval Sea Systems Command (NAVSEA) Contract N00024-17-D-6421, Task Order 5101070, “GNSS Signal Performance and Anomaly Analysis.”

Performance is assessed relative to selected assertions in the 2020 Standard Positioning Service (SPS) Performance Standard (SPS PS 2020 or SPS PS 2020) [1]. The SPS PS 2020 presents assertions that are supported by the USSF 2nd Navigation Warfare Squadron (2 NWS) (formerly known as 2nd Space Operations Squadron (2 SOPS)) operational procedures, tempered with technical and operational margin.

Chapter 2 of this report contains a tabular summary of performance evaluated against the metrics provided in the SPS PS 2020. Chapter 3 presents a more detailed explanation of the analysis conducted in evaluating each assertion. The assertions are presented in order of appearance in the SPS PS 2020. Appendix A contains additional results of interest that are, in some cases, beyond the assertions. Appendix B contains supporting data used to interpret the results. Appendix C contains notes on how the analysis was conducted. Appendix D contains acronyms and abbreviations.

The SPS PS 2020 defines services delivered through multiple signals. The signals and signal combinations defined are listed in Table 1.1. For the SPS PS 2020, the signals and signal combinations duplicate SPS PS 2020 Table 2.2-2. LNAV refers to the GPS Legacy Navigation Message [2] and CNAV refers to the GPS Civil Navigation Message [2], [3].

Table 1.1: SPS SIS Signal Combinations Covered by SPS PS 2020

One Carrier Single Frequency (SF)	Two Carriers Dual Frequency (DF)	Three Carriers Triple Frequency (TF)
C/A-code + LNAV Data	(C/A + CM)-codes + CNAV Data	(C/A + CM + I5)-codes + CNAV Data
CM-code + CNAV Data	(C/A + CL)-codes + CNAV Data	(C/A + CL + I5)-codes + CNAV Data
CL-code + CNAV Data	(C/A + CM+CL)-codes + CNAV Data	(C/A + CM+CL + I5)-codes + CNAV Data
(CM+CL)-codes + CNAV Data	(C/A + I5)-codes + CNAV Data	(C/A + CM + Q5)-codes + CNAV Data
I5-code + CNAV Data	(C/A + Q5)-codes + CNAV Data	(C/A + CL + Q5)-codes + CNAV Data
Q5-code + CNAV Data	(C/A + I5+Q5)-codes + CNAV Data	(C/A + CM+CL + Q5)-codes + CNAV Data
(I5+Q5)-codes + CNAV Data		(C/A + CM+CL + I5+Q5)-codes + CNAV Data

Table 1.1 contains a large number of signal combinations; however, it is possible to evaluate the performance of all these combinations by focusing on a subset that examines each unique signal and each unique message. The signal combinations directly examined in this report are listed below and are described in further detail in Appendix C.1.

- Single-frequency L1 C/A with LNAV messages
- Dual-frequency L1 C/A + L2C with CNAV messages
- Dual-frequency L1 C/A + L5Q with CNAV messages

Each GPS SV is identified by space vehicle number (SVN) and belongs to a block. Four different GPS space vehicle (SV) blocks were operational during 2024 (Block IIR, Block IIR-M, Block IIF, GPS III). Not all blocks are capable of broadcasting all signals. The signals broadcast by each block and the navigation message data on each signal are shown in Table 1.2.

Table 1.2: SPS SIS Signals Present by Block in 2024

Block	SVNs	# SVs	L1 C/A (LNAV)	L2C (CNAV)	L5Q (CNAV)
IIR	43, 44, 45, 51, 56, 59, 61	7	✓	–	–
IIR-M	48, 50, 52, 53, 55, 57, 58	7	✓	✓	–
IIF	62, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73	11	✓	✓	✓
III	74, 75, 76, 77, 78, 79	6	✓	✓	✓

The assertions examined include those related to coverage, accuracy, integrity, continuity, availability, and position/time domain. These metrics, with the exception of position/time domain, are limited to the signal-in-space (SIS) and do not address atmospheric errors, receiver errors, or errors due to the user environment (e.g., multipath errors, local obstructions, and foliage).

This report addresses assertions in the SPS PS 2020 that can be verified by anyone with knowledge of standard GPS data analysis practices, familiarity with the relevant signal specifications [2] [3], and access to a GPS data archive (such as that available via the International Global Navigation Satellite System (GNSS) Service (IGS)) [4].

The majority of the assertions related to user range error (URE) values are evaluated by comparison of the SV clock and position broadcast and precise representations. Broadcast clock and position data (BC&P) are provided by the GPS LNAV and CNAV message data. Precise clock and position data (PC&P) are provided by a precise orbit calculated after the time of interest. The URE calculation process requires both BC&P and PC&P and is detailed in Appendix C.2.

Many of the analyses are conducted at a 30 second cadence due to the fact that the GPS LNAV clock, ephemeris, and integrity (CEI) data repeats every 30 s and that is the highest frequency with which quantities such as satellite health can change. This 30 s cadence was selected prior to CNAV data processing and has been retained for consistency, even though the CEI data repetition rate for CNAV is different.

Observation data from tracking stations were used to cross-check the URE values and to evaluate non-URE assertions, such as those found in Section 3.4 (Continuity), Section 3.5 (Availability), and Section 3.6 (Position/Time Domain). The assertions focus on SIS performance, which is not directly observable from ground tracking locations. To mitigate this issue, this performance review uses ionospherically-corrected dual-frequency observation data. In these cases, data from two networks were used. The two networks considered were the National Geospatial-Intelligence Agency (NGA) Monitor Station Network (MSN) [5] and a subset of the tracking stations that contribute to the IGS. A subset of the IGS network was selected to cover a wide geographic distribution, prioritizing receivers with high quality clocks and long term data availability. The geographic distribution of these stations is shown in Figure 1.1. The selection of these sets of stations ensures continuous, simultaneous observation of all SVs by multiple stations.

Navigation message data used in this report were collected from the NGA MSN. The collection and selection of navigation message data are described in general terms in Appendix C.3.

The majority of the metrics in this report are evaluated on either a per SV basis or for the full constellation. The metrics associated with continuity and availability are defined with respect to the slot definitions in SPS PS 2020. The slot definitions are stated in terms of either the Baseline 24 constellation, which consists of six orbital planes with four slots per plane, or the Expandable 24 constellation, in which six of the 24 slots may be occupied by two SVs. Of the operational SVs, 30 were located in the Expandable 24 constellation throughout 2024. The SVs in excess of those located in defined slots are assigned to locations in planes in accordance with operational considerations. There was one such satellite during 2024. For additional information on slot definitions, see Appendix B.3.

Each GPS SV is identified by a pseudo-random noise (PRN) ID in addition to SVN. PRNs are assigned to SVs for periods of time. A given SV may be assigned different PRNs at different times during its operational life. The SVN represents the permanent unique identifier for each SV. As the number of active SVs has increased to the total number of PRNs available, thirty-two [1], PRNs are now being used by multiple SVs within a given year (but by no more than one SV at a time). In general, we list the SVN first and the PRN second because the SVN is the unique identifier of the two.

The SVN-to-PRN relationships were provided by the GPS Master Control Station (MCS). Other useful summaries of this information may be found on the U.S. Coast Guard Navigation Center website [6]. See Appendix B.1 for a summary of the SVN-to-PRN mapping for 2024.

For the operational signals addressed in this report, only results obtained when a signal was trackable and transmitting a healthy indication are included in the analysis.

L5 was pre-operational during the period covered by this report and although L5 signals indicate an unhealthy status, that does not imply inaccuracy. In order to derive results for signal combinations that include L5, the L5 signal was treated as if it were healthy whenever the corresponding L1 C/A signal indicated a healthy condition. In some cases when L1 C/A transitions between health states, the corresponding L5 navigation message transition may lag by a few minutes. As a result, the L5 signal is regarded as unavailable after a L1 C/A transition from unhealthy-to-healthy until the next L5 navigation message is received. For assertions related to L5, the navigation message was obtained from L5I while the observation data was obtained from L5Q.

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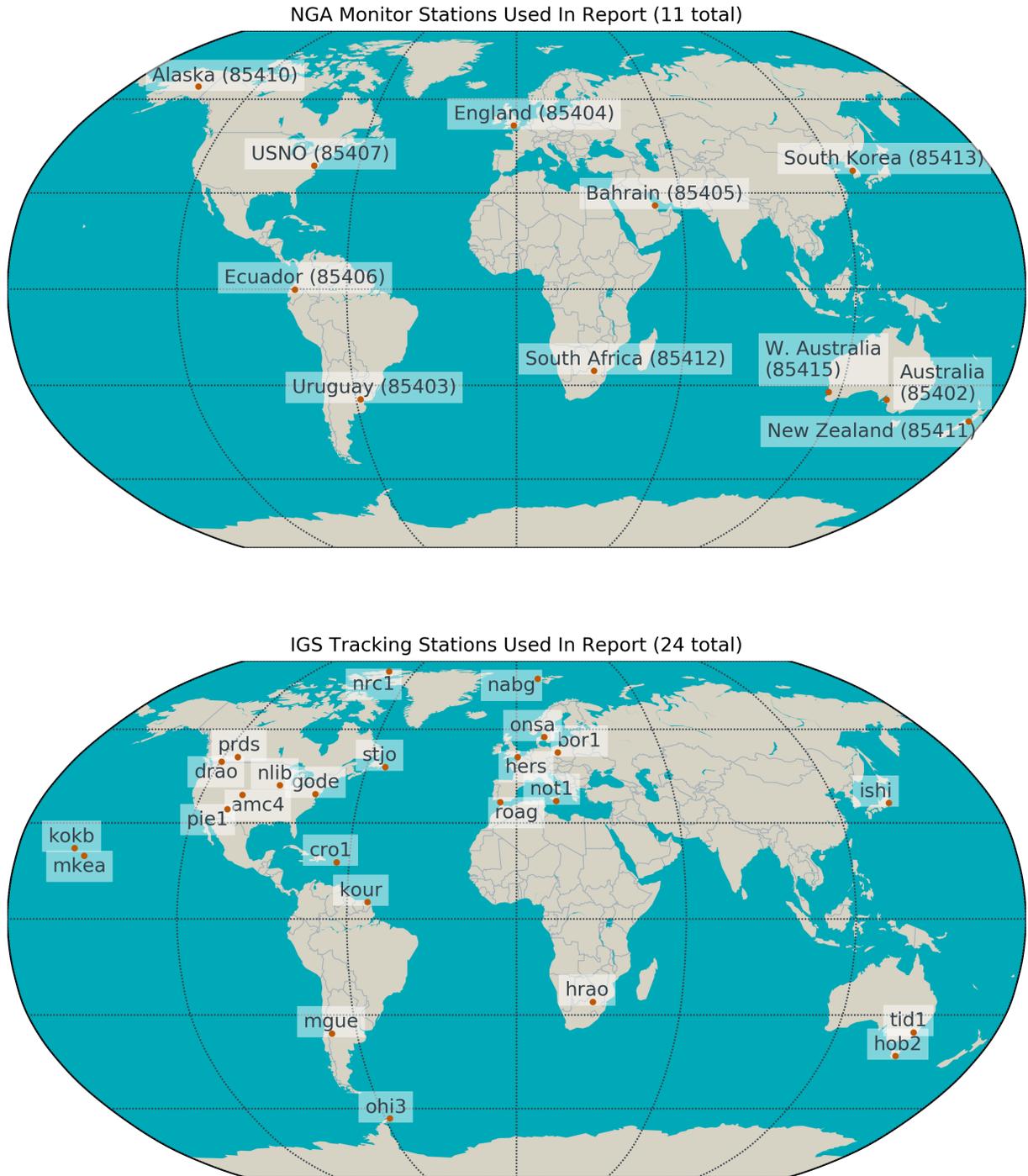


Figure 1.1: Maps of the Networks of Stations Used in this Report

Chapter 2

Summary of 2024 Results Utilizing SPS PS 2020 Metrics

Table 2.1 provides a summary of the assertions defined in SPS PS 2020. The table is annotated to show which assertions are evaluated in this report and the status of each assertion.

All of the LNAV SPS PS 2020 assertions examined in this report were met in 2024. All of the CNAV SPS PS 2020 assertions except two examined in this report were met in 2024. The exceptions were the integrity and P_{sat} assertions. For more information, see Section 3.3.1 and Section 3.3.3.

Details regarding each result may be found in Chapter 3. All abbreviations used in Table 2.1 may be found in Appendix D. The reasons some assertions were not evaluated are provided in the text.

Table 2.1: Summary of SPS PS 2020 Metrics Examined for 2024

SPS PS 2020 Section	SPS PS 2020 Assertion	Signal Status			System Status
		L1 C/A	L1 C/A + L2C	L1 C/A + L5Q	
3.3.1 SIS Per-Satellite Coverage	100% Coverage of terrestrial service volume	-	-	-	NE
3.3.2 SIS Constellation Coverage	100% Coverage of terrestrial service volume	-	-	-	✓
3.4.1 SIS URE Accuracy	≤ 7.0 m 95% Global statistic URE during normal operations over all AODs	✓	✓	✓	-
	≤ 9.7 m 95% Global statistic URE during normal operations at any AOD	✓	✓	✓	-
	≤ 3.8 m 95% Global statistic URE during normal operations at zero AOD	✓	✓	✓	-
	≤ 30 m 99.94% Global statistic URE during normal operations	✓	✓	✓	-
	≤ 30 m 99.79% Worst case single point statistic URE during normal operations	✓	✓	✓	-
	≤ 388 m 95% Global statistic URE during extended operations after 14 days without upload	NE	-	-	-
	≤ 2.0 m 95% Global statistic URE during normal operations over all AODs for the ensemble of constellation slots	✓	✓	✓	-
3.4.2 SIS URRE Accuracy	≤ 0.006 m/s 95% Global statistic URRE over any 3-second interval during normal operations at any AOD	✓	✓	✓	-
3.4.3 SIS URAE Accuracy	≤ 0.002 m/s ² 95% Global statistic URAE over any 3-second interval during normal operations at any AOD	✓★	✓★	✓★	-
3.4.4 SIS UTCOE Accuracy	≤ 30 nsec 95% Global statistic UTCOE during normal operations at any AOD	✓	✓	✓	-
3.5.1 SIS Instantaneous URE Integrity	≤ 1 × 10 ⁻⁵ Probability over any hour of exceeding the NTE tolerance without a timely alert	✓	✗	✗	-
3.5.4 SIS Instantaneous UTCOE Integrity	≤ 1 × 10 ⁻⁵ Probability over any hour of exceeding the NTE tolerance without a timely alert during normal operations	✓	✓	✓	-
3.5.5 SIS Instantaneous P _{sat} and P _{const}	≤ 1 × 10 ⁻⁵ Fraction of time when the SPS SIS instantaneous URE exceeds the NTE tolerance without a timely alert (P _{sat})	✓	✗	✓	-
	≤ 1 × 10 ⁻⁸ Fraction of time when the SPS SIS instantaneous URE from two or more satellites exceeds the NTE tolerance due to a common cause without a timely alert (P _{const})	✓	✓	✓	-
3.6.1 SIS Continuity - Unscheduled Failure Interruptions	≥ 0.9998 Probability over any hour of not losing the SPS SIS availability from the slot due to unscheduled interruption	✓	-	-	-
3.6.3 Status and Problem Reporting	Appropriate NANU issued at least 48 hours prior to a scheduled event for 95% of the events	✓	✓	✓	-
3.7.1 SIS Per-Slot Availability	≥ 0.957 Probability that (a) a slot in the baseline 24-slot will be occupied by a satellite broadcasting a healthy SF C/A-Code SPS SIS, or (b) a slot in the expanded configuration will be occupied by a pair of satellites each broadcasting a healthy SF C/A-Code SPS SIS	✓	-	-	-
3.7.2 SIS Constellation Availability	≥ 0.98 Probability that at least 21 slots out of the 24 slots will be occupied by a satellite (or pair of satellites for expanded slots) broadcasting a healthy SF C/A-Code SPS SIS	✓	-	-	-
	≥ 0.99999 Probability that at least 20 slots out of the 24 slots will be occupied by a satellite (or pair of satellites for expanded slots) broadcasting a healthy SF C/A-Code SPS SIS	✓	-	-	-
3.7.3 Operational Satellite Counts	≥ 0.95 Probability that the constellation will have at least 24 operational satellites regardless of whether those operational satellites are located in slots or not	-	-	-	✓
3.8.1 PDOP Availability	≥ 98% Global PDOP of 6 or less	✓	-	-	-
	≥ 88% Worst site PDOP of 6 or less	✓	-	-	-
3.8.2 Position Service Availability	≥ 99% Horizontal service availability, average location	✓	-	-	-
	≥ 99% Vertical service availability, average location	✓	-	-	-
	≥ 90% Horizontal service availability, worst-case location	✓	-	-	-
	≥ 90% Vertical service availability, worst-case location	✓	-	-	-
3.8.3 Position/Velocity/Time Service Accuracy	≤ 8 m 95% Horizontal error, global average position accuracy	✓	-	-	-
	≤ 13 m 95% Vertical error, global average position accuracy	✓	-	-	-
	≤ 15 m 95% Horizontal error, worst site position accuracy	✓	-	-	-
	≤ 33 m 95% Vertical error, worst site position accuracy	✓	-	-	-
	≤ 0.2 m/s 95% Velocity error, any axis	✓	-	-	-
	≤ 30 nsec Time transfer error 95% of the time	✓	-	-	-

✓ Assertion met ✗ Assertion not met NE Assertion not evaluated - No assertion
 L5 is pre-operational and set unhealthy. ★ Met for all but two SV-months.
 See Chapter 1 for more information. See Section 3.2.7 for details.

Table 2.2: References of SPS PS 2020 Metrics Examined for 2024

SPS PS 2020 Section	SPS PS 2020 Assertion	Report Section
3.3.1 SIS Per-Satellite Coverage	100% Coverage of terrestrial service volume	3.1.1
3.3.2 SIS Constellation Coverage	100% Coverage of terrestrial service volume	3.1.2
3.4.1 SIS URE Accuracy	≤ 7.0 m 95% Global statistic URE during normal operations over all AODs	3.2.1
	≤ 9.7 m 95% Global statistic URE during normal operations at any AOD	3.2.2
	≤ 3.8 m 95% Global statistic URE during normal operations at zero AOD	3.2.3
	≤ 30 m 99.94% Global statistic URE during normal operations	3.2.4
	≤ 30 m 99.79% Worst case single point statistic URE during normal operations	
	≤ 388 m 95% Global statistic URE during extended operations after 14 days without upload	3.2.5
	≤ 2.0 m 95% Global statistic URE during normal operations over all AODs for the ensemble of constellation slots	3.2.1.1
3.4.2 SIS URRE Accuracy	≤ 0.006 m/s 95% Global statistic URRE over any 3-second interval during normal operations at any AOD	3.2.6
3.4.3 SIS URAE Accuracy	≤ 0.002 m/s ² 95% Global statistic URAE over any 3-second interval during normal operations at any AOD	3.2.7
3.4.4 SIS UTCOE Accuracy	≤ 30 nsec 95% Global statistic UTCOE during normal operations at any AOD	3.2.8
3.5.1 SIS Instantaneous URE Integrity	$\leq 1 \times 10^{-5}$ Probability over any hour of exceeding the NTE tolerance without a timely alert	3.3.1
3.5.4 SIS Instantaneous UTCOE Integrity	$\leq 1 \times 10^{-5}$ Probability over any hour of exceeding the NTE tolerance without a timely alert during normal operations	3.3.2
3.5.5 SIS Instantaneous P_{sat} and P_{const}	$\leq 1 \times 10^{-5}$ Fraction of time when the SPS SIS instantaneous URE exceeds the NTE tolerance without a timely alert (P_{sat})	3.3.3
	$\leq 1 \times 10^{-8}$ Fraction of time when the SPS SIS instantaneous URE from two or more satellites exceeds the NTE tolerance due to a common cause without a timely alert (P_{const})	
3.6.1 SIS Continuity - Unscheduled Failure Interruptions	≥ 0.9998 Probability over any hour of not losing the SPS SIS availability from the slot due to unscheduled interruption	3.4.1
3.6.3 Status and Problem Reporting	Appropriate NANU issued at least 48 hours prior to a scheduled event for 95% of the events	3.4.2.1
3.7.1 SIS Per-Slot Availability	≥ 0.957 Probability that (a) a slot in the baseline 24-slot will be occupied by a satellite broadcasting a healthy SF C/A-Code SPS SIS, or (b) a slot in the expanded configuration will be occupied by a pair of satellites each broadcasting a healthy SF C/A-Code SPS SIS	3.5.1
3.7.2 SIS Constellation Availability	≥ 0.98 Probability that at least 21 slots out of the 24 slots will be occupied by a satellite (or pair of satellites for expanded slots) broadcasting a healthy SF C/A-Code SPS SIS	3.5.2
	≥ 0.99999 Probability that at least 20 slots out of the 24 slots will be occupied by a satellite (or pair of satellites for expanded slots) broadcasting a healthy SF C/A-Code SPS SIS	
3.7.3 Operational Satellite Counts	≥ 0.95 Probability that the constellation will have at least 24 operational satellites regardless of whether those operational satellites are located in slots or not	3.5.3
3.8.1 PDOP Availability	$\geq 98\%$ Global PDOP of 6 or less	3.6.1.1
	$\geq 88\%$ Worst site PDOP of 6 or less	
3.8.2 Position Service Availability	$\geq 99\%$ Horizontal service availability, average location	3.6.2
	$\geq 99\%$ Vertical service availability, average location	
	$\geq 90\%$ Horizontal service availability, worst-case location	
	$\geq 90\%$ Vertical service availability, worst-case location	
3.8.3 Position/Velocity/Time Service Accuracy	≤ 8 m 95% Horizontal error, global average position accuracy	3.6.3
	≤ 13 m 95% Vertical error, global average position accuracy	
	≤ 15 m 95% Horizontal error, worst site position accuracy	
	≤ 33 m 95% Vertical error, worst site position accuracy	
	≤ 0.2 m/s 95% Velocity error, any axis	
	≤ 30 nsec Time transfer error 95% of the time	3.6.4

Chapter 3

Discussion of 2024 Results Utilizing SPS PS 2020 Metrics

While Chapter 2 summarizes the status of the SPS PS 2020 metrics for 2024, the statistics and trends reported in this chapter provide both additional information and support for those conclusions.

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3.1 SIS Coverage

3.1.1 Per-Satellite Coverage

SIS per-satellite coverage is asserted in Section 3.3.1 of the SPS PS 2020. The following standard is provided (from Table 3.3-1):

- *“100% Coverage of Terrestrial Service Volume”*

This means that the direction of the Earth coverage beam of each GPS SV will be managed such that the beam will cover the terrestrial service volume visible to that SV, providing at least the minimum required received power at every point in its terrestrial footprint. This assertion is not evaluated at this time. Within the GPS Control Segment, the operators have various tools which enable them to monitor and control SV pointing. Monitoring this assertion external to the control segment will require both SV-specific antenna gain pattern information and calibrated power observations. The potential for evaluation may be examined in future reports.

3.1.2 Constellation Coverage

SIS constellation coverage is asserted in Section 3.3.2 of the SPS PS 2020. The following standard is provided (from Table 3.3-2):

- *“100% Coverage of Terrestrial Service Volume”*

This assertion is interpreted to mean that a user will have at least four SVs transmitting a healthy or marginal signal visible at any moment. This is evaluated as part of the examination of DOP (see Section 3.6). The condition was true throughout the year, thus the assertion is met for 2024.

3.2 SIS Accuracy

SIS URE accuracy is asserted in Section 3.4 of the SPS PS 2020. The following standards (from Tables 3.4-1 through 3.4-4 in the SPS PS 2020) are considered in this report for each SPS SIS signal combination, per SPS PS 2020 Table 2.2-2, each with different constraints for age of data (AOD):

- “ ≤ 7.0 m 95% Global Statistic URE during Normal Operations over all AODs”
- “ ≤ 9.7 m 95% Global Statistic URE during Normal Operations at Any AOD”
- “ ≤ 3.8 m 95% Global Statistic URE during Normal Operations at Zero AOD”
- “ ≤ 30 m 99.94% Global Statistic URE during Normal Operations”
- “ ≤ 30 m 99.79% Worst Case Single Point Statistic URE during Normal Operations”
- “ ≤ 388 m 95% Global Statistic URE during Extended Operations after 14 Days without Upload (C/A only)”
- “ ≤ 2.0 m 95% Global Statistic URE during Normal Operations over all AODs for the ensemble of constellation slots”
- “ ≤ 0.006 m/s 95% Global Statistic URRE over any 3-second interval during Normal Operations at Any AOD”
- “ ≤ 0.002 m/s² 95% Global Statistic URAE over any 3-second interval during Normal Operations at Any AOD”
- “ ≤ 30 nsec 95% Global Statistic UTCOE during Normal Operations at Any AOD”

SIS accuracy values are included in the statistics only when the SV is healthy (except for L5, as described in Chapter 1). Throughout this report, an SV is considered healthy based on the definition in SPS PS 2020 Section 2.3.2.

The URE statistics presented in this report are based on a comparison of the BC&P against the PC&P (see Appendix C).

3.2.1 URE Over All AOD

The 95th percentile global statistic URE over all AODs is the performance standard URE metric that is most closely related to a user's observations. This is associated with the SPS PS 2020 Section 3.4 metric:

- *“Each SPS SIS Component Combination per Table 2.2-2:
≤ 7.0 m 95% Global Statistic URE during Normal Operations over all AODs”*

This metric can be decomposed into several pieces to better understand the process, as follows:

- *Each SPS SIS Component Combination per Table 2.2-2* - This applies to all signal combinations.
- *7.0 m* - This is the limit against which to test.
- *95%* - This is the statistical measure applied to the data. In this case, there is a sufficiently large number of samples to allow direct sorting of the results across time and selection of the 95th percentile.
- *Global Statistic URE* - This refers to examining the URE across the field-of-view and across time. The brute force methods described in SPS PS 2020 A.4.11 are applicable to computing statistics over field-of-view and over time.
- *during Normal Operations* - This is a constraint related to normal vs. extended navigation mode operations. See IS-GPS-200 20.3.4.4 [2] and Appendix A.4 of this report.
- *over all AODs* - This constraint means that the global statistic URE is considered at each evaluation time regardless of the AOD at the evaluation time. A more detailed explanation of the AOD and how this quantity is computed can be found in Appendix A.2.

In addition, the following general statements in Section 3.4 of SPS PS 2020 have a bearing on this calculation:

- These statistics are “per SV” - that is, they apply to the signal from each satellite, not for averages across the constellation.
- *“The ergodic period contains the minimum number of samples such that the sample statistic is representative of the population statistic. Under a one-upload-per-day scenario, for example, the traditional approximation of the URE ergodic period is 30 days.”* (SPS PS 2020 Section 3.4, Note 2)

In order to evaluate this assertion, it is practical to compute a sufficiently dense spatial grid of instantaneous SIS URE values across the period of interest separated by uniform timesteps (see Appendix C.2.3 for details), and then select the 95th percentile values from this set.

In this case, the time steps are 5 minutes and the period of interest is monthly. The monthly period approximates the suggested 30 day period while conforming to a familiar time scale. We have computed the monthly statistic regardless of the number of available days in each month. We have also identified SV-months with fewer than 25 days of availability to note any SV-month with significantly less data than expected.

The results are organized as follows: Table 3.1 and Figure 3.1 contain L1 C/A single-frequency results, Table 3.2 and Figure 3.2 contain L1 C/A + L2C dual-frequency results, and Table 3.3 and Figure 3.3 contain L1 C/A + L5Q dual-frequency results.

Tables 3.1, 3.2, and 3.3 contain the monthly 95th percentile values of the instantaneous SIS URE values based on the assumptions and constraints described above. For each SV, the worst value across the year is marked in red. Additionally, monthly 95th percentile values for each block and the full constellation are provided.

In all cases, no values exceed the stated threshold of 7.0 m, and so this assertion is met for 2024.

Figures 3.1, 3.2, and 3.3 provide a summary of these results for the entire constellation. A number of points are evident from this set of tables and figures:

1. All SVs meet the performance assertion of the SPS PS 2020, even when only the worst performing month is considered. The worst value for each SV (indicated by the upper extent of the range bars) is less than half the threshold.
2. For most of the SVs, the value of the 95th percentile SIS URE metric is relatively stable over the course of the year, as indicated by relatively small range bars.
3. The “best” SVs are those which cluster at or below the 1.0 m level and whose range variation is small.
4. SVN 72/PRN 8 (Block IIF) and SVN 73/PRN 10 (Block IIF) were the two SVs operating on a cesium frequency standard until February, resulting in higher URE values for January and February.
5. The highest URE values for the constellation as a whole occurred in January. This is due to operational changes that led to lower URE values later in the year [7].

Table 3.1: Monthly 95th Percentile Values of L1 C/A SIS Instantaneous URE for All SVs in Meters

SVN	PRN	Block	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2024
43	13	IIR	0.96	0.71	0.69	0.64	0.63	0.63	0.70	0.69	0.67	0.66	0.73	0.62	0.69
44	22	IIR	0.81	0.84	0.75	0.67	0.82	0.87	0.76	0.73	0.78	0.79	0.92	0.85	0.81
45	21	IIR	1.11	1.21	1.18	1.15	1.13	1.14	1.34	1.11	1.30	1.32	1.25	1.29	1.22
48	7	IIR-M	1.04	0.79	0.67	0.65	0.68	0.77	0.68	0.72	0.78	0.73	0.77	0.70	0.75
50	5	IIR-M	0.63	0.74	0.53	0.62	0.72	0.76	0.76	0.63	0.66	0.58	0.68	0.64	0.67
51	20	IIR	1.27	1.09	1.07	1.17	1.08	0.91	0.92	1.04	1.13	1.15	1.05	1.02	1.09
52	31	IIR-M	0.86	0.69	0.74	0.87	0.60	0.55	0.55	0.62	0.80	0.73	0.77	0.52	0.71
53	17	IIR-M	1.09	0.79	0.64	0.56	0.66	0.62	0.62	0.58	0.63	0.59	0.62	0.67	0.68
55	15	IIR-M	0.74	0.52	0.48	0.51	0.53	0.68	0.73	0.74	0.71	0.63	0.51	0.68	0.66
56	16	IIR	0.72	0.59	0.58	0.64	0.72	0.70	0.63	0.70	0.74	0.76	0.63	0.73	0.69
57	29	IIR-M	0.92	0.77	0.66	0.70	0.63	0.60	0.65	0.68	0.68	0.66	0.62	0.60	0.69
58	12	IIR-M	0.64	0.64	0.58	0.74	0.78	0.76	0.70	0.63	0.62	0.55	0.64	0.56	0.67
59	19	IIR	1.35	1.25	1.11	1.20	1.21	1.24	1.15	1.08	1.14	1.26	1.26	1.34	1.23
61	2	IIR	1.41	1.12	1.13	1.14	1.02	1.08	1.09	1.12	1.14	1.17	1.15	1.17	1.16
62	25	IIF	0.85	0.93	0.72	0.89	1.11	0.98	0.94	0.93	0.82	0.76	0.90	0.86	0.92
64	30	IIF	0.80	0.76	0.83	0.67	0.54	0.56	0.47	0.62	0.71	0.70	0.83	0.79	0.72
65	24	IIF	0.61	0.71	0.56	0.56	0.51	0.40	0.48	0.52	0.68	0.50	0.53	0.46	0.56
66	27	IIF	–	0.73	0.79	0.83	0.59	0.69	0.72	0.69	0.80	0.85	0.66	0.72	0.74
67	6	IIF	0.74	0.91	0.92	1.13	1.03	0.93	0.81	0.93	1.01	0.86	0.82	0.68	0.93
68	9	IIF	0.83	0.67	0.73	0.49	0.56	0.53	0.59	0.65	0.52	0.38	0.46	0.55	0.61
69	3	IIF	1.52	1.09	1.14	1.32	1.12	1.19	1.10	1.08	1.10	1.00	1.18	0.88	1.14
70	32	IIF	0.85	0.76	0.54	0.66	0.69	0.69	0.68	0.70	0.82	0.74	0.78	0.76	0.74
71	26	IIF	0.61	0.47	0.58	0.52	0.62	0.61	0.53	0.48	0.74	0.66	0.83	0.66	0.62
72	8	IIF	2.33	2.63	0.67	0.61	0.59	0.61	0.62	0.51	0.61	0.60	0.58	0.56	1.16
73	10	IIF	1.87	2.12	0.58	0.56	0.58	0.64	0.61	0.66	0.71	0.63	0.66	0.58	0.90
74	4	III	0.71	0.83	0.87	0.60	0.67	0.76	0.76	0.82	1.00	0.73	0.72	0.65	0.78
75	18	III	0.88	0.86	0.91	0.87	0.92	0.84	0.68	0.80	0.94	0.92	0.85	0.74	0.86
76	23	III	0.98	0.85	0.84	0.85	0.81	0.78	0.74	0.77	0.76	0.84	0.84	0.81	0.83
77	14	III	0.90	0.86	0.81	0.90	1.04	0.99	0.92	0.81	0.81	0.93	0.92	0.87	0.91
78	11	III	0.90	0.96	0.94	0.96	0.80	0.95	0.88	0.86	0.98	0.98	0.90	0.87	0.92
79	28	III	0.68	0.70	0.88	0.90	0.73	0.67	0.74	0.78	0.93	0.91	0.90	0.89	0.83
Block IIR/IIR-M			1.12	0.99	0.94	1.00	0.96	0.94	0.95	0.92	1.00	1.03	1.00	1.03	0.99
Block IIF			1.25	1.18	0.79	0.91	0.84	0.83	0.77	0.80	0.82	0.75	0.79	0.72	0.84
GPS III			0.87	0.86	0.88	0.88	0.86	0.86	0.81	0.81	0.92	0.90	0.87	0.83	0.86
All SVs			1.09	0.99	0.89	0.95	0.91	0.89	0.87	0.86	0.93	0.93	0.92	0.90	0.93

Notes: Values not present indicate that the satellite was not healthy throughout this period. Months during which an SV was healthy for less than 25 days are shown shaded. Months with the highest SIS instantaneous URE for a given SV are colored red. The column labeled “2024” is the 95th percentile over all the days in the year. The four rows at the bottom are the monthly 95th percentile values over various sets of SVs.

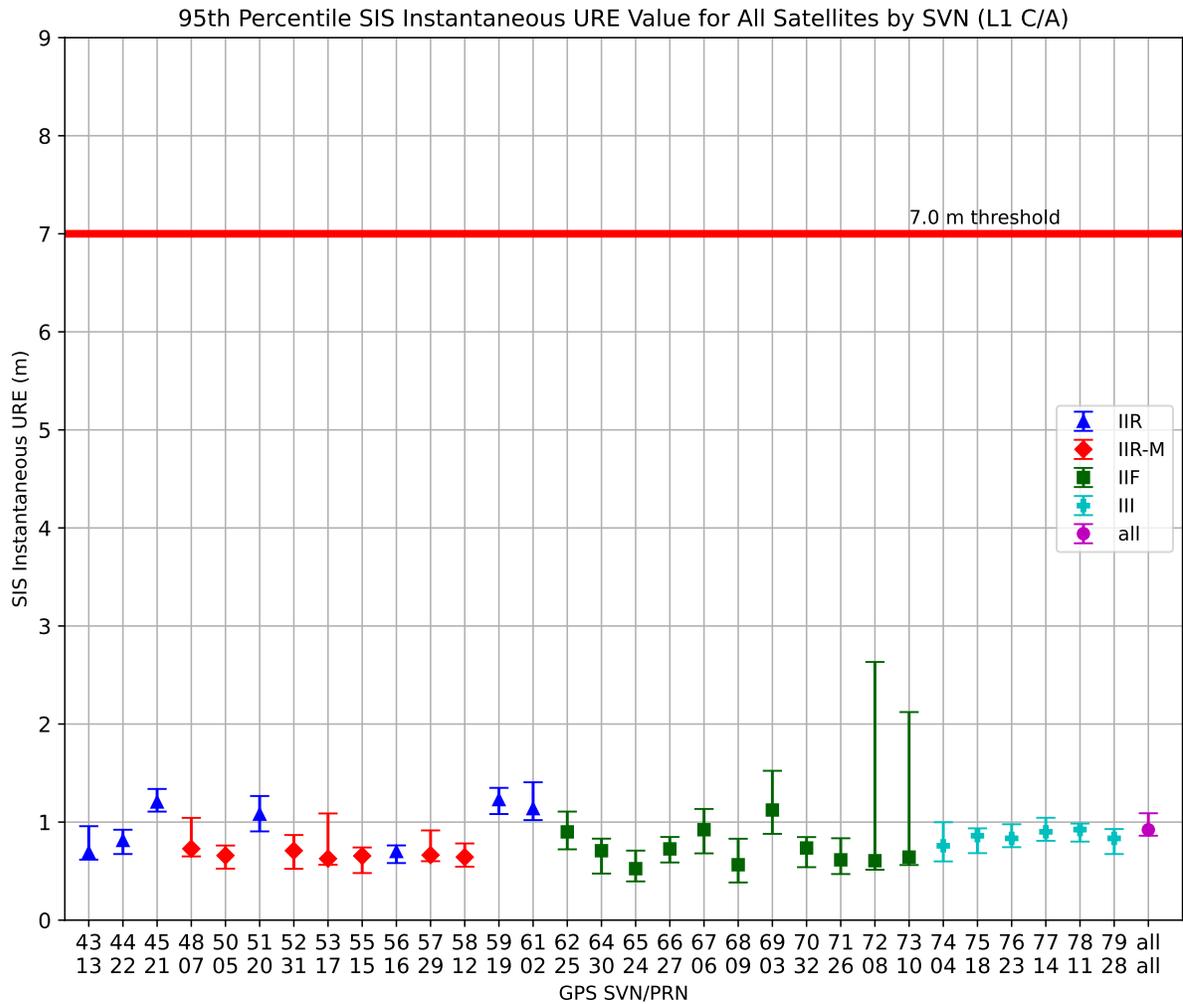


Figure 3.1: Range of the L1 C/A Monthly 95th Percentile Values for All SVs

Notes: Each SVN with valid data is shown sequentially along the horizontal axis. The median value of the monthly 95th percentile SIS URE is displayed as a point on each of the vertical bars. The minimum and maximum of the monthly 95th percentile SIS URE for 2024 are shown by whiskers at the top and bottom of each vertical bar. Color and shape distinguish between the Block IIR, Block IIR-M, Block IIF, and GPS III SVs. The red horizontal line at 7.0 m indicates the upper bound given by the SPS PS 2020 Section 3.4 performance metric. The marker for “all” represents the monthly 95th percentile values across all satellites.

Table 3.2: Monthly 95th Percentile Values of L1 C/A + L2C SIS Instantaneous URE for All SVs in Meters

SVN	PRN	Block	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2024
48	7	IIR-M	1.13	0.81	0.61	0.63	0.66	0.73	0.61	0.69	0.78	0.66	0.70	0.67	0.72
50	5	IIR-M	0.62	0.69	0.46	0.60	0.52	0.48	0.50	0.46	0.44	0.49	0.57	0.52	0.53
52	31	IIR-M	0.89	0.72	0.67	0.75	0.58	0.54	0.54	0.61	0.73	0.60	0.56	0.49	0.65
53	17	IIR-M	1.11	0.74	0.58	0.54	0.65	0.64	0.57	0.53	0.64	0.61	0.55	0.61	0.65
55	15	IIR-M	0.53	0.52	0.46	0.48	0.49	0.46	0.47	0.44	0.47	0.36	0.43	0.44	0.47
57	29	IIR-M	0.88	0.76	0.61	0.70	0.64	0.62	0.63	0.65	0.64	0.73	0.61	0.55	0.68
58	12	IIR-M	0.58	0.55	0.53	0.72	0.71	0.63	0.60	0.56	0.55	0.51	0.52	0.47	0.58
62	25	IIF	0.53	0.53	0.46	0.67	0.62	0.54	0.48	0.34	0.45	0.48	0.53	0.42	0.52
64	30	IIF	0.72	0.82	0.69	0.64	0.51	0.42	0.43	0.54	0.67	0.56	0.50	0.44	0.61
65	24	IIF	0.66	0.80	0.53	0.51	0.46	0.35	0.35	0.42	0.60	0.48	0.43	0.44	0.52
66	27	IIF	–	0.84	0.71	0.74	0.55	0.57	0.53	0.43	0.69	0.74	0.66	0.75	0.67
67	6	IIF	0.62	0.69	0.58	0.64	0.55	0.47	0.57	0.55	0.70	0.66	0.53	0.52	0.59
68	9	IIF	0.57	0.64	0.57	0.58	0.41	0.46	0.59	0.60	0.55	0.48	0.55	0.68	0.57
69	3	IIF	1.57	0.81	0.72	0.86	0.76	0.81	0.71	0.74	0.80	0.65	0.93	0.76	0.83
70	32	IIF	0.73	0.65	0.54	0.51	0.44	0.54	0.52	0.50	0.48	0.36	0.36	0.40	0.52
71	26	IIF	0.53	0.47	0.50	0.68	0.64	0.64	0.51	0.48	0.73	0.63	0.97	0.62	0.63
72	8	IIF	2.45	2.73	0.68	0.59	0.69	0.63	0.59	0.47	0.54	0.50	0.55	0.52	1.19
73	10	IIF	1.98	2.40	0.54	0.50	0.63	0.73	0.59	0.58	0.60	0.57	0.64	0.61	0.90
74	4	III	0.38	0.50	0.53	0.31	0.33	0.40	0.44	0.53	0.70	0.47	0.38	0.33	0.47
75	18	III	0.50	0.53	0.60	0.47	0.54	0.46	0.36	0.42	0.52	0.43	0.46	0.40	0.48
76	23	III	0.63	0.56	0.54	0.56	0.52	0.53	0.39	0.47	0.59	0.45	0.48	0.49	0.53
77	14	III	0.56	0.54	0.50	0.56	0.66	0.59	0.52	0.42	0.47	0.60	0.51	0.46	0.54
78	11	III	0.47	0.52	0.47	0.47	0.41	0.57	0.49	0.46	0.56	0.58	0.53	0.55	0.52
79	28	III	0.45	0.42	0.60	0.63	0.52	0.52	0.53	0.54	0.66	0.55	0.55	0.61	0.56
Block IIR-M			0.85	0.70	0.56	0.63	0.61	0.59	0.57	0.57	0.63	0.58	0.57	0.54	0.62
Block IIF			1.31	1.16	0.60	0.63	0.59	0.59	0.54	0.53	0.63	0.58	0.62	0.60	0.65
GPS III			0.52	0.52	0.54	0.52	0.52	0.52	0.47	0.48	0.60	0.52	0.50	0.51	0.52
All SVs			0.92	0.80	0.57	0.61	0.58	0.57	0.53	0.53	0.62	0.56	0.58	0.56	0.61

Notes: Values not present indicate that the satellite was not healthy throughout this period. Months during which an SV was healthy for less than 25 days are shown shaded. Months with the highest SIS instantaneous URE for a given SV are colored red. The column labeled “2024” is the 95th percentile over all the days in the year. The four rows at the bottom are the monthly 95th percentile values over various sets of SVs.

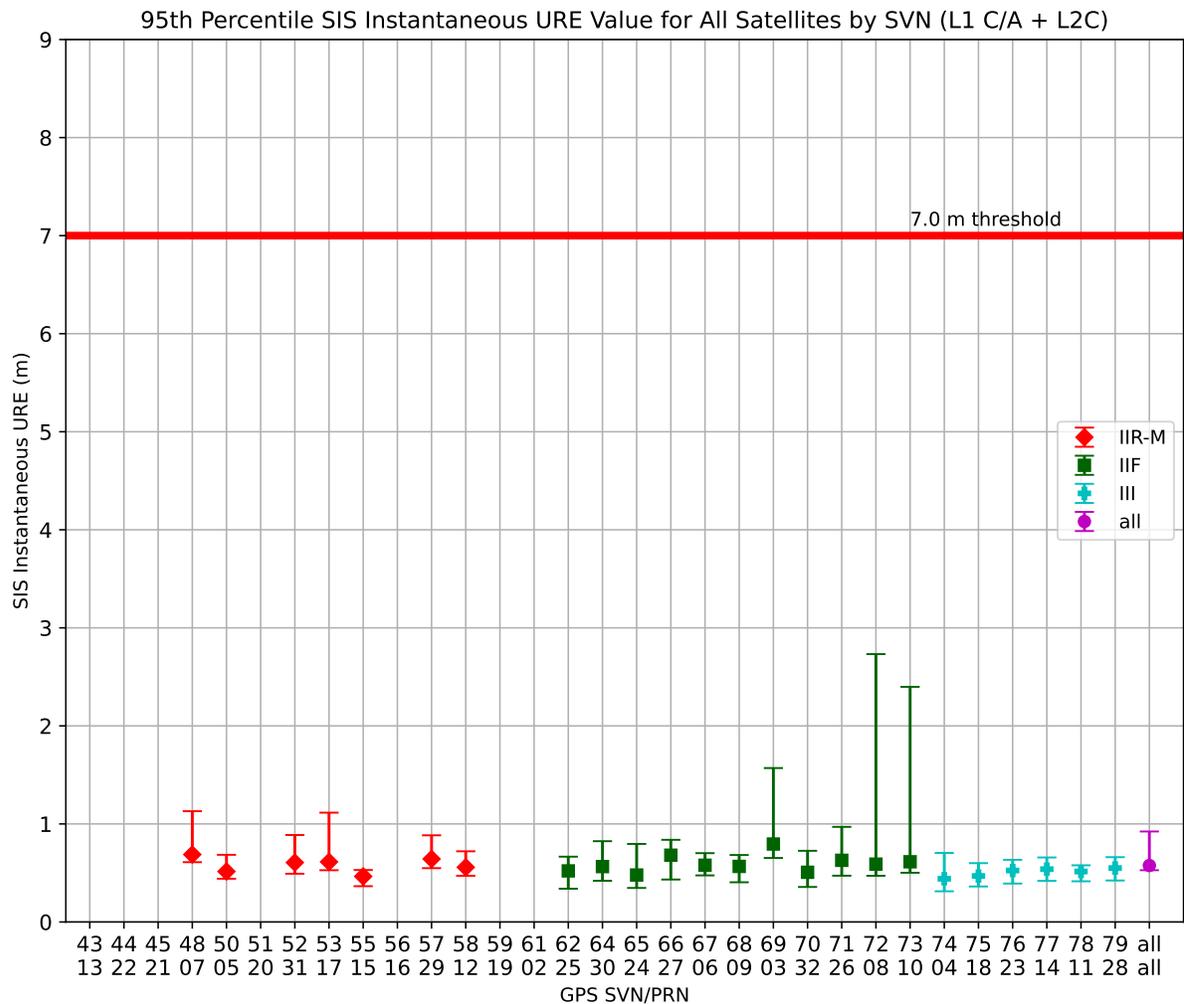


Figure 3.2: Range of the L1 C/A + L2C Monthly 95th Percentile Values for All SVs

Notes: Each SVN with valid data on at least one of the dual-frequency signals is shown sequentially along the horizontal axis. Satellites without valid data on both of the dual-frequency signals are not plotted. The median value of the monthly 95th percentile SIS URE is displayed as a point on each of the vertical bars. The minimum and maximum of the monthly 95th percentile SIS URE for 2024 are shown by whiskers at the top and bottom of each vertical bar. Color and shape distinguish between the Block IIR-M, Block IIF, and GPS III SVs. The red horizontal line at 7.0 m indicates the upper bound given by the SPS PS 2020 Section 3.4 performance metric. The marker for “all” represents the monthly 95th percentile values across all satellites.

Table 3.3: Monthly 95th Percentile Values of L1 C/A + L5Q SIS Instantaneous URE for All SVs in Meters

SVN	PRN	Block	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2024
62	25	IIF	0.96	1.00	0.72	0.81	1.01	0.86	0.72	0.74	0.79	0.79	0.88	0.82	0.86
64	30	IIF	0.85	0.74	0.83	0.67	0.72	0.74	0.65	0.79	0.71	0.75	0.92	0.80	0.78
65	24	IIF	0.96	0.91	0.91	0.94	1.10	1.00	0.88	0.99	1.18	1.08	0.99	1.00	1.02
66	27	IIF	–	1.29	1.30	1.33	1.05	1.10	1.12	1.04	1.27	1.33	1.19	1.22	1.22
67	6	IIF	0.75	0.74	0.64	0.69	0.63	0.55	0.63	0.60	0.72	0.69	0.57	0.60	0.65
68	9	IIF	0.60	0.60	0.50	0.47	0.36	0.40	0.47	0.48	0.45	0.35	0.44	0.55	0.49
69	3	IIF	1.61	0.93	0.84	0.88	0.82	0.88	0.77	0.80	0.85	0.73	0.99	0.87	0.91
70	32	IIF	0.85	0.78	0.59	0.56	0.50	0.61	0.54	0.55	0.51	0.41	0.42	0.44	0.59
71	26	IIF	0.66	0.63	0.62	0.78	0.72	0.74	0.63	0.65	0.88	0.75	1.07	0.72	0.75
72	8	IIF	2.41	2.72	0.75	0.66	0.74	0.65	0.60	0.48	0.55	0.52	0.54	0.54	1.17
73	10	IIF	1.94	2.34	0.63	0.59	0.67	0.68	0.59	0.64	0.75	0.67	0.70	0.53	0.91
74	4	III	0.73	0.82	0.87	0.55	0.65	0.73	0.77	0.85	1.05	0.78	0.71	0.64	0.80
75	18	III	0.77	0.80	0.81	0.77	0.88	0.80	0.64	0.74	0.83	0.75	0.75	0.68	0.78
76	23	III	0.98	0.98	0.94	0.93	0.89	0.86	0.79	0.86	0.86	0.84	0.84	0.86	0.90
77	14	III	0.98	0.98	0.90	0.97	1.07	0.99	0.93	0.83	0.91	1.01	0.94	0.90	0.96
78	11	III	0.97	1.05	0.96	0.97	0.93	1.09	1.01	0.96	1.07	1.09	1.08	1.10	1.04
79	28	III	0.93	1.01	1.18	1.20	1.07	1.08	1.10	1.10	1.21	1.12	1.11	1.18	1.12
Block IIF			1.28	1.24	0.89	0.93	0.88	0.87	0.83	0.83	0.98	0.97	0.93	0.89	0.94
GPS III			0.92	0.98	0.98	1.01	0.97	0.98	0.98	0.94	1.03	1.02	1.01	1.05	0.99
All SVs			1.08	1.08	0.94	0.97	0.93	0.92	0.91	0.88	1.01	0.99	0.97	0.98	0.97

Notes: Values not present indicate that the satellite was not healthy throughout this period. Months during which an SV was healthy for less than 25 days are shown shaded. Months with the highest SIS instantaneous URE for a given SV are colored red. The column labeled “2024” is the 95th percentile over all the days in the year. The three rows at the bottom are the monthly 95th percentile values over various sets of SVs.

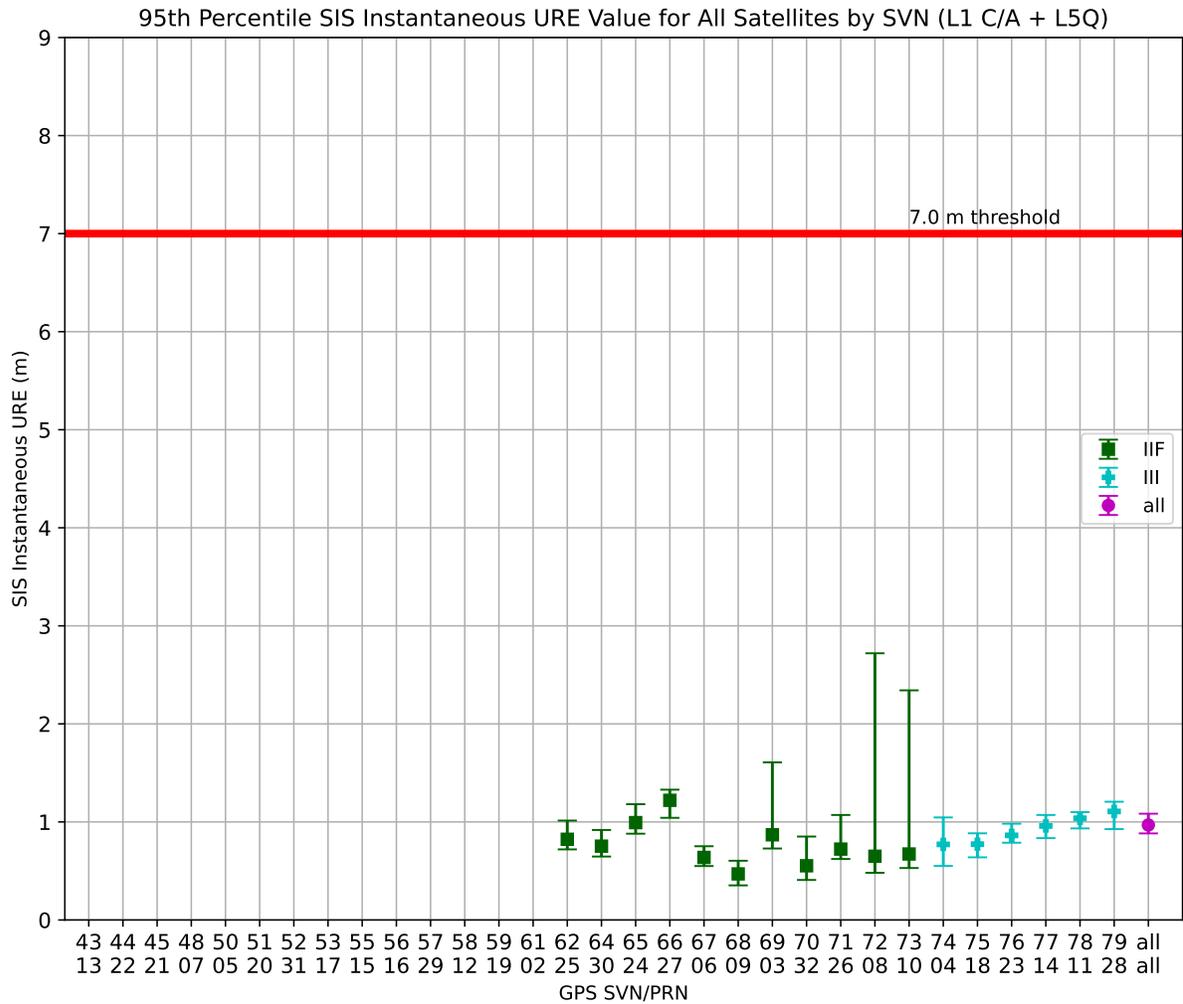


Figure 3.3: Range of the L1 C/A + L5Q Monthly 95th Percentile Values for All SVs

Notes: Each SVN with valid data on at least one of the dual-frequency signals is shown sequentially along the horizontal axis. Satellites without valid data on both of the dual-frequency signals are not plotted. The median value of the monthly 95th percentile SIS URE is displayed as a point on each of the vertical bars. The minimum and maximum of the monthly 95th percentile SIS URE for 2024 are shown by whiskers at the top and bottom of each vertical bar. Color and shape distinguish between the Block IIF and GPS III SVs. The red horizontal line at 7.0 m indicates the upper bound given by the SPS PS 2020 Section 3.4 performance metric. The marker for “all” represents the monthly 95th percentile values across all satellites.

We computed the differences between the dual-frequency (L1 C/A + L2C, L1 C/A + L5Q) and the single-frequency (L1 C/A) monthly 95th percentile values. This allowed us to examine the relative differences between the various signal combinations. Figure 3.4 plots these differences for each SV.

Note that each of the signal combinations were processed with the same broadcast ephemeris and the same precise ephemeris. The differences in the URE results are due to the inter-signal correction (ISC) values, the differential code bias (DCB) values being used to evaluate the correctness of the ISCs, and the inter-signal correction process. Appendix C.2.2 describes the manner in which the ISCs, the DCBs, and the process interact. For purposes of Figure 3.4, it is sufficient to note that the L1 C/A values are used as reference and the range of the differences against the monthly values for the other signal combinations are shown.

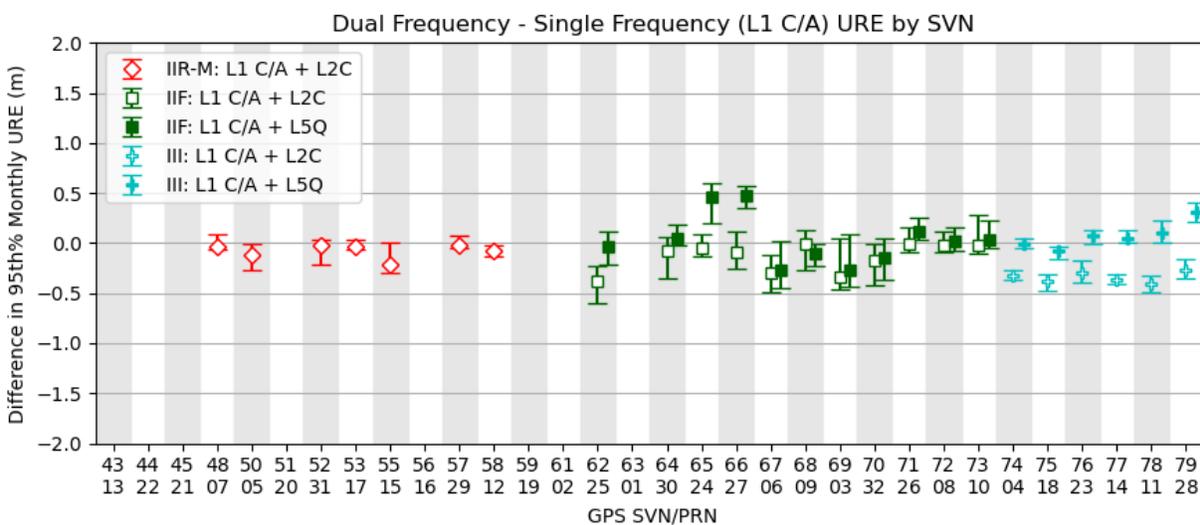


Figure 3.4: Range of Differences in Monthly Values between Dual-Frequency and L1 C/A UREs for All SVs

Notes: Each SVN with valid data is shown sequentially along the horizontal axis. The median value of the difference of monthly 95th percentile SIS URE is displayed as a point on each of the vertical bars. The minimum and maximum of the difference for 2024 are shown by whiskers at the top and bottom of each vertical bar. Color and shape distinguish between the Block IIR-M, Block IIF, and GPS III SVs.

3.2.1.1 Constellation URE

The constellation accuracy is asserted in the last row of Table 3.4-1 of Section 3.4.1 of the SPS PS 2020:

- “ ≤ 2.0 m 95% Global Statistic URE during normal operations over all AODs for the ensemble of constellation slots”

This assertion is unique among the SIS URE assertions in that it is across all the SVs occupying slots rather than by each individual SV.

We make the case that this assertion is met by examining the overall constellation values. This is a slightly larger population than the set of SVs that occupy slots. When the by-SV values and overall constellation values are sufficiently below the threshold, the assertion for the ensemble of constellation slots is considered met. As shown in Appendix B, of the 31 operational SVs, there were 30 SVs in slots throughout the year.

Figures 3.1, 3.2, and 3.3 show the constellation results as the rightmost range of values labeled “all” in the legend, shown in magenta.

Tables 3.1, 3.2, and 3.3 contain the monthly 95th percentile values for all operational SVs in the final row. These values are replicated in Table 3.4 below.

The highest URE values for the constellation occurred in January. This is due to operational changes that led to lower URE values later in the year [7].

As seen, these values are all below 2.0 m, thus the assertion is met. This is asserted to be true for all signal combinations in SPSPS20 Table 2.2-2.

Table 3.4: Monthly 95th Percentile Values of Constellation SIS Instantaneous URE for All Signals in Meters

Signal	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2024
L1 C/A	1.09	0.99	0.89	0.95	0.91	0.89	0.87	0.86	0.93	0.93	0.92	0.90	0.93
L1 C/A + L2C	0.92	0.80	0.57	0.61	0.58	0.57	0.53	0.53	0.62	0.56	0.58	0.56	0.61
L1 C/A + L5Q	1.08	1.08	0.94	0.97	0.93	0.92	0.91	0.88	1.01	0.99	0.97	0.98	0.97

Notes: Months with the highest SIS instantaneous URE for a given signal or signal combination are colored red. The column labeled “2024” is the 95th percentile over all the days in the year.

3.2.2 URE at Any AOD

The next URE metric considered is the calculation of URE at any AOD. This is associated with the following SPS PS 2020 Section 3.4 metric:

- “ ≤ 9.7 m 95% Global Statistic URE during Normal Operations at Any AOD”

This metric may be decomposed in a manner similar to the metrics for URE over all AOD. The key differences are the term “at any AOD” and the change in the threshold value. The phrase “at any AOD” is interpreted to mean that at any AOD where sufficient data can be collected to constitute a reasonable statistical set, the value of the required statistic should be ≤ 9.7 m. See Appendix A.2 for a discussion of how the AOD is computed.

To examine this requirement, the set of 30 s instantaneous SIS RMS (root mean square) URE values was computed as described in Appendix C.2.4, and processed as described in Appendix A.5. In summary, the SIS RMS URE values for each satellite for the entire year were divided into bins based on 15 minute intervals of AOD. The 95th percentile values for each bin were selected and the results were plotted as a function of the AOD in hours.

Figures 3.5 through 3.10 show up to four curves:

- 95th percentile URE vs. AOD for:
 - Blue: L1 C/A
 - Magenta: L1 C/A + L2C
 - Cyan: L1 C/A + L5Q
- Green: count of points in each bin vs. AOD for L1 C/A

Where multiple curves are present, the biases between the curves are a result of the influence of the ISC and DCB values on the URE calculation process. See Appendix C.2.2 for details.

The count of points is shown for L1 C/A, which is representative of the curves for other signal combinations, as the unhealthy periods for all signals for a given SV are coordinated to within a few minutes.

For satellites with an average of one upload per day, the count of points in each bin is roughly constant from the time the upload becomes available until about 24 hours AOD. This corresponds to a plateau of the green curve. For satellites averaging more than one upload per day, the green curve will show a left-hand peak decreasing to the right. This is a result of there being fewer points at higher AOD due to the more frequent uploads. The vertical scales on Figures 3.5 through 3.10 and the figures in Appendix A.5 have been constrained to a fixed range to aid in comparisons among the charts. Any satellites that were operational for only part of the year will have a lower number of points per bin.

The representative best performers for Block IIR, Block IIR-M, Block IIF, and GPS III are shown in Figures 3.5, 3.7, 3.9, and 3.11. These are SVN 56/PRN 16, SVN 55/PRN 15, SVN 68/PRN 9, and SVN 74/PRN 4, respectively.

For all blocks, several SVs have similarly good results. Best performers exhibit a low and flat distribution of AODs, and the UREs appear to hold nearly constant with time, at least to the point that the distribution (represented by the green curve) shows a marked reduction in the number of points.

Figures 3.6, 3.8, 3.10, and 3.12 show the worst performing Block IIR, Block IIR-M, Block IIF, and GPS III SVs. These are SVN 45/PRN 21, SVN 48/PRN 7, SVN 69/PRN 3, and SVN 78/PRN 11, respectively.

Note that the distribution of AOD samples for the worst performing satellites are biased toward shorter values of AOD, which indicates that uploads are occurring more frequently than once-per-day. GPS III satellites have more similar results between best and worst performers than the other blocks.

The plots for all satellites are contained in Appendix A.5. While there are differences between individual satellites, all the results are well within the assertion for this metric.

3.2.3 URE at Zero AOD

Another URE metric considered is the calculation of URE at Zero Age of Data (ZAOD). This is associated with the SPS PS 2020 Section 3.4 metric:

- “ ≤ 3.8 m 95% Global Statistic URE during Normal Operations at Zero AOD”

This metric may be decomposed in a manner similar to the previous two metrics. The key differences are the term “at Zero AOD” and the change in the threshold value.

The broadcast ephemeris is never available to user equipment at ZAOD due to the delays inherent in preparing the broadcast ephemeris and uploading it to the SV. However, we can still make a case that this assertion is met by examining the 95th percentile SIS RMS URE value at 15 minutes AOD. These values are represented by the left-most data point on the solid lines shown in Figure 3.5 through Figure 3.12. The ZAOD values should be slightly smaller than the 15 minute AOD values or, at worst, roughly comparable. Inspection of the 15 minute AOD values shows that the values for all SVs are well within the 3.8 m value associated with the assertion. Therefore, the assertion is considered fulfilled.

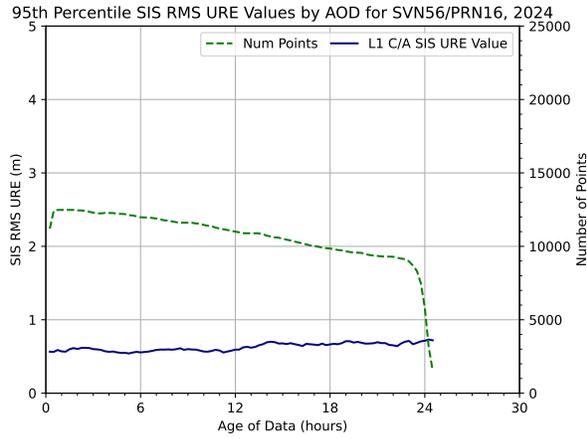


Figure 3.5: Best Performing Block IIR SV by URE Over Any AOD

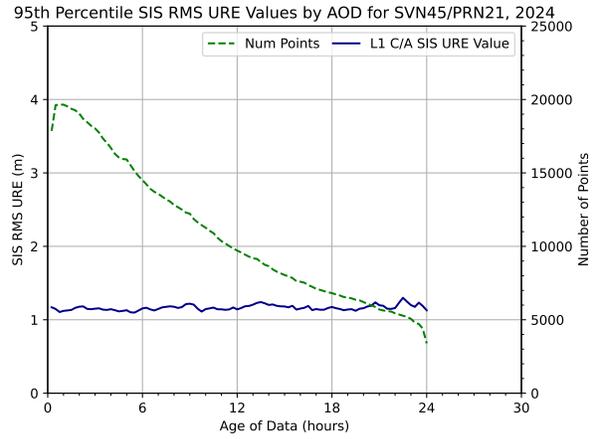


Figure 3.6: Worst Performing Block IIR SV by URE Over Any AOD

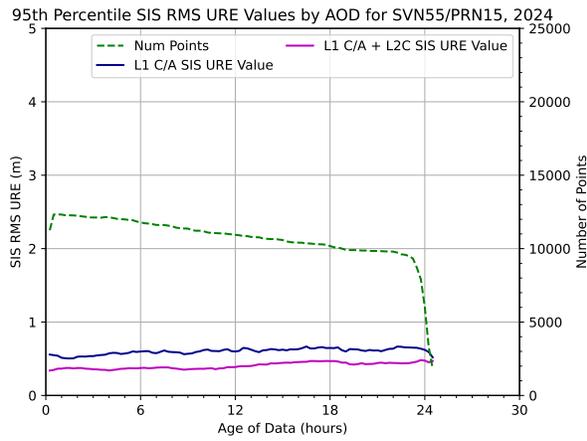


Figure 3.7: Best Performing Block IIR-M SV by URE Over Any AOD

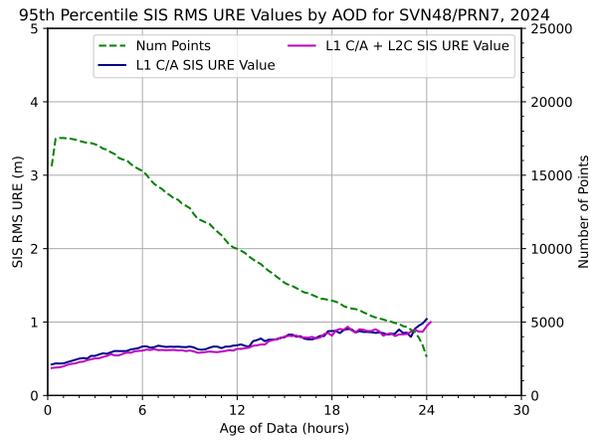


Figure 3.8: Worst Performing Block IIR-M SV by URE Over Any AOD

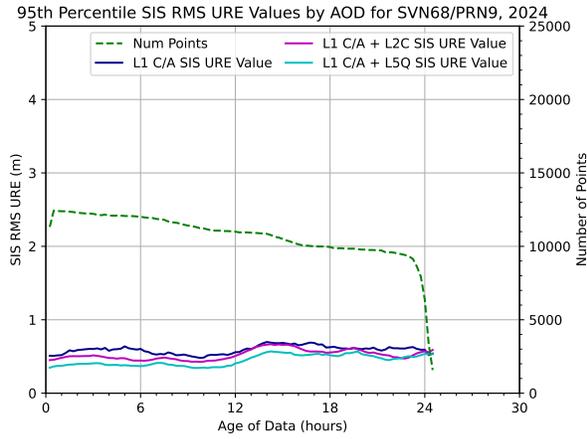


Figure 3.9: Best Performing Block IIF SV by URE Over Any AOD

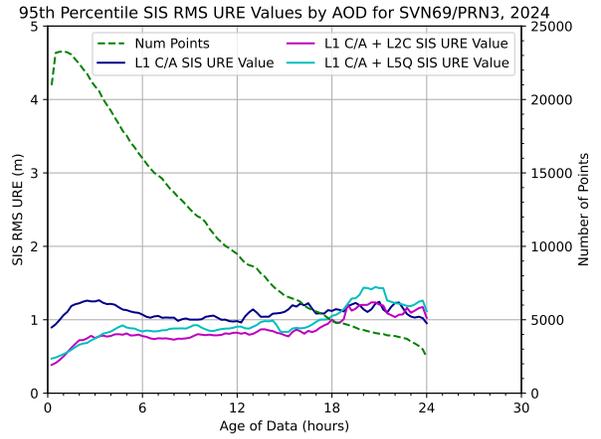


Figure 3.10: Worst Performing Block IIF SV by URE Over Any AOD

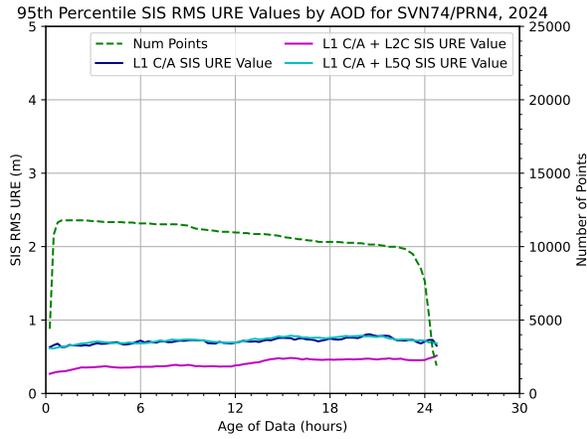


Figure 3.11: Best Performing GPS III SV by URE Over Any AOD

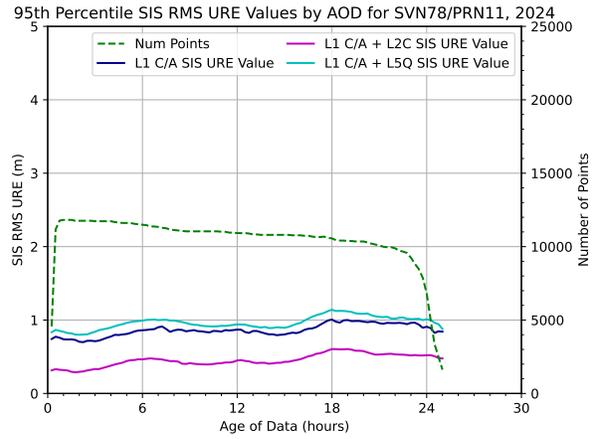


Figure 3.12: Worst Performing GPS III SV by URE Over Any AOD

3.2.4 URE Bounding

The SPS PS 2020 asserts the following requirements:

- “ ≤ 30 m 99.94% Global Statistic URE during Normal Operations”
- “ ≤ 30 m 99.79% Worst Case Single Point Statistic URE during Normal Operations”

The conditions and constraints do not clearly enumerate averaging periods. Therefore, the instantaneous SIS URE values computed as part of the evaluation described in Appendix C.2.3 were checked for events exceeding the 30 m threshold. This provides a set of 596 instantaneous SIS URE values distributed across the area visible to a given SV at each 5 min epoch, which yields a set of 60 million values per SV per year.

However, there are limitations to our technique of estimating UREs that are worth noting, such as fits across orbit/clock discontinuities, thrust events, and clock run-offs. These are discussed in Appendix C.2.5. As a result of these limitations, a set of L1 P(Y) + L2 P(Y) observed range deviations (ORDs) was also examined as a cross-check.

The ORDs were formed using the NGA observation data collected to support the position accuracy analysis described in Section 3.6.3. In the case of ORDs, the observed range is differenced from the range predicted by the geometric distance from the known station position to the SV location derived from the broadcast ephemeris. The ORDs are similar to the instantaneous SIS URE in that both represent the error along a specific line-of-sight. However, the ORDs are not true SIS measurements due to the presence of residual tropospheric effects, multipath, and receiver noise. The selected stations are geographically distributed such that at least two sets of observations are available for each SV at all times. As a result, any actual SV problems that would lead to a violation of this assertion will produce large ORDs from multiple stations.

There was one event with values that exceeded the 30 m threshold for SVN 48/PRN 7 for 14 minutes on L1 C/A and 13.5 minutes on L1 C/A + L2C. Appendix A.6.2 contains additional information on this event.

For SVN 48/PRN 7 in 2024:

- The 99.94% Global Statistic URE was:
 - 1.994 m on L1 C/A
 - 1.843 m on L1 C/A + L2C
- The 99.79% Worst Case Single Point Statistic URE was:
 - 1.781 m on L1 C/A
 - 1.646 m on L1 C/A + L2C

Based on these results, these assertions are considered satisfied.

3.2.5 URE After 14 Days Without Upload

The SPS PS 2020 provides the following assertion regarding URE after 14 days without an upload for single-frequency C/A-code:

- “ ≤ 388 m 95% Global Statistic URE during Extended Operations after 14 Days without Upload”

There were no periods in 2024 during which SVs were transmitting a healthy signal while operating after 14 days without an upload. As a result, this assertion was not evaluated.

3.2.6 URRE Over All AOD

The SPS PS 2020 provides the following assertion for the user range rate error (URRE):

- “ ≤ 0.006 m/sec 95% Global Statistic URRE over any 3-second interval during Normal Operations at Any AOD”

This is subject to the same general constraints from SPS PS 2020 Section 3.4 as the URE assertions.

The user range rate is the time-derivative of the range between the SV and the user; that is the rate of change of the range. For the case of a stationary user and an orbiting satellite, the actual user range rate will vary throughout a pass, but will be a smooth, continuous function. In reality, the measurement of user range, and therefore, the ability to derive the user range rate is limited by the noise of the SV frequency standard (clock) and the receiver frequency standard, along with other effects. The URRE measures the impact of the noise of the SV frequency standard on the SIS. For more information see SPS PS 2020 Section A.4.7.

The URRE cannot be evaluated by comparison of the BC&P to the PC&P. This is due to two factors:

1. as described in Note 1 to SPS PS 2020 Table 3.4-2, the primary contributing factor to the URRE is the noise from the SV frequency standards, and
2. the assertion states “*over any 3-second interval.*”

In the precise ephemerides used for the PC&P, the noise due to the SV clocks is smoothed over long periods. As a result, the comparison of BC&P and PC&P derivatives will not reveal short term (i.e. 3 s) changes in SV clock behavior.

To address this, a different evaluation process is used. This process uses the PC&P along with the measured carrier phase observations and the known station positions to form the URRE values by differencing the range errors. The carrier phase observations have much lower noise than the pseudorange values, and because both phase and range are based on the same SV clock and the same receiver clock, the result will be a more precise measurement of the range rate error.

Dual-frequency observations are used to reduce ionospheric errors and a global tropospheric model is used to reduce tropospheric errors in order to adhere as closely as practical to the constraint that the results are to be based on SIS. The observation data available in 2024 included observations from L1 P(Y) and L2 P(Y) at a 0.5 s rate.

The preceding steps create a time-series of URRE values over 3 s intervals for each SV-receiver combination. This implies that the individual values are not fully independent as each 3 s interval spans multiple observations with the earliest/latest of each set contributing to the adjacent URRE value time periods. These results are grouped for each month for a given SV for all healthy, trackable periods. The 95th% of the absolute value of each monthly dataset for each satellite is computed. These results are shown in Table 3.5 and Figure 3.13.

While the results are labeled as “URRE” in Table 3.5 and Figure 3.13, it should be noted that these are actually user-equivalent range rate errors (UERRE), as defined in Note 2 to SPS PS 2020 Table 3.4-2. Therefore, the results shown are the root-sum-square of the SIS-caused URRE and receiver-caused rate errors due to receiver thermal noise, local environmental issues such as multipath, and the effect of the frequency standard that is associated with the receiver.

The values in Table 3.5 are all less than 6 mm/sec except for the value associated with SVN 72/PRN 8 in January. The values for September are higher than for other months due to known receiver effects. SVN 72/PRN 8 (Block IIF) and SVN 73/PRN 10 (Block IIF) were the two SVs operating on a cesium frequency standard until February. To explore this further, the URRE values were also computed using only data from the NGA monitor station at U.S. Naval Observatory (USNO) which uses a frequency reference that is traceable to an ensemble of hydrogen maser frequency standards. This reduces the noise for the receiver portion of the UERRE but limits the visibility to the periods in which each SV is tracked by that station. When the data from the station at USNO are processed in isolation, the results show an improvement of 3% for SVN 72/PRN 8 in January. As a result, all the values are less than 6 mm/sec. This indicates that the portion of UERRE attributable to SVN 72/PRN 8 is within the threshold.

The requirement is considered to be met in 2024 for all SVs.

Table 3.5: Monthly 95th Percentile Values of L1 P(Y) + L2 P(Y) SIS Instantaneous URRE for All SVs in mm/s

SVN	PRN	Block	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
43	13	IIR	3.77	3.97	4.15	3.71	3.65	3.68	3.95	3.93	4.38	3.94	3.77	3.93
44	22	IIR	3.57	3.51	3.49	3.52	3.55	3.48	3.52	3.55	3.69	3.70	3.56	3.63
45	21	IIR	3.89	3.96	4.09	4.02	3.98	3.91	3.98	4.06	4.34	4.25	4.08	4.19
48	7	IIR-M	3.23	3.37	3.43	3.39	3.44	3.17	3.23	3.36	3.60	3.57	3.33	3.23
50	5	IIR-M	4.91	4.93	4.84	4.90	5.00	4.96	4.68	4.83	5.07	5.16	4.99	5.19
51	20	IIR	3.49	3.51	3.44	3.46	3.50	3.43	3.43	3.46	3.74	3.70	3.51	3.58
52	31	IIR-M	2.97	3.10	3.14	3.08	3.06	2.95	2.99	3.05	3.36	3.24	2.93	2.95
53	17	IIR-M	3.77	3.60	3.40	3.41	3.53	3.61	3.63	3.53	3.64	3.62	3.45	3.71
55	15	IIR-M	3.43	3.60	3.39	3.23	3.30	3.35	3.42	3.43	3.56	3.39	3.25	3.35
56	16	IIR	3.71	3.60	3.69	3.89	4.02	3.76	3.65	3.57	3.97	4.12	4.06	3.91
57	29	IIR-M	3.29	3.26	3.26	3.17	3.23	3.24	3.26	3.22	3.42	3.33	3.13	3.32
58	12	IIR-M	3.41	3.50	3.44	3.43	3.62	3.38	3.23	3.17	3.50	3.62	3.54	3.44
59	19	IIR	3.56	3.61	3.50	3.45	3.48	3.47	3.51	3.53	3.71	3.62	3.45	3.56
61	2	IIR	3.34	3.36	3.37	3.40	3.41	3.39	3.43	3.47	3.64	3.64	3.42	3.43
62	25	IIF	2.62	2.73	2.66	2.58	2.66	2.58	2.54	2.58	2.80	2.74	2.48	2.52
64	30	IIF	2.52	2.55	2.47	2.52	2.57	2.51	2.51	2.53	2.79	2.73	2.54	2.48
65	24	IIF	2.80	2.98	2.82	2.75	2.88	2.80	2.79	2.82	3.01	2.98	2.75	2.76
66	27	IIF	–	2.74	2.66	2.66	2.75	2.72	2.71	2.74	2.95	2.88	2.66	2.67
67	6	IIF	2.43	2.49	2.40	2.40	2.52	2.46	2.44	2.49	2.76	2.65	2.47	2.46
68	9	IIF	2.48	2.53	2.44	2.47	2.56	2.50	2.48	2.52	2.82	2.75	2.40	2.43
69	3	IIF	2.49	2.55	2.41	2.43	2.53	2.48	2.43	2.46	2.71	2.69	2.46	2.44
70	32	IIF	2.48	2.54	2.46	2.49	2.56	2.48	2.48	2.51	2.68	2.64	2.42	2.47
71	26	IIF	2.62	2.69	2.58	2.60	2.69	2.65	2.62	2.64	2.89	2.77	2.58	2.62
72	8	IIF	6.03	5.97	2.63	2.63	2.74	2.70	2.66	2.68	2.95	2.81	2.62	2.62
72*	8*	IIF	5.86	5.78	2.07	2.04	2.22	2.16	2.02	2.02	2.03	2.02	2.03	2.00
73	10	IIF	4.04	3.37	2.56	2.58	2.67	2.60	2.59	2.61	2.73	2.77	2.56	2.59
74	4	III	2.74	2.76	2.78	2.83	2.80	2.76	2.79	2.82	3.14	3.07	2.73	2.78
75	18	III	2.76	2.77	2.80	2.83	2.83	2.78	2.83	2.86	3.04	3.07	2.82	2.83
76	23	III	2.82	2.81	2.82	2.86	2.90	2.83	2.89	2.93	3.11	3.07	2.83	2.87
77	14	III	2.89	2.81	2.81	2.87	2.87	2.82	2.88	2.91	3.05	3.09	2.91	2.96
78	11	III	2.67	2.73	2.72	2.72	2.77	2.72	2.74	2.78	3.05	3.00	2.77	2.77
79	28	III	2.74	2.79	2.79	2.82	2.82	2.74	2.79	2.83	3.14	3.08	2.76	2.80
All SVs			3.39	3.33	3.15	3.14	3.19	3.13	3.13	3.16	3.40	3.35	3.15	3.18

Notes: Values not present indicate that the satellite was not healthy throughout this period. Months during which an SV was healthy for less than 25 days are shown shaded. Months with the highest SIS instantaneous URRE for a given SV are colored red. The row at the bottom is the monthly 95th percentile values over all SVs. The * on the second row for SVN 72/PRN 08 indicates use of USNO data only. See Section 3.2.6 for more information.

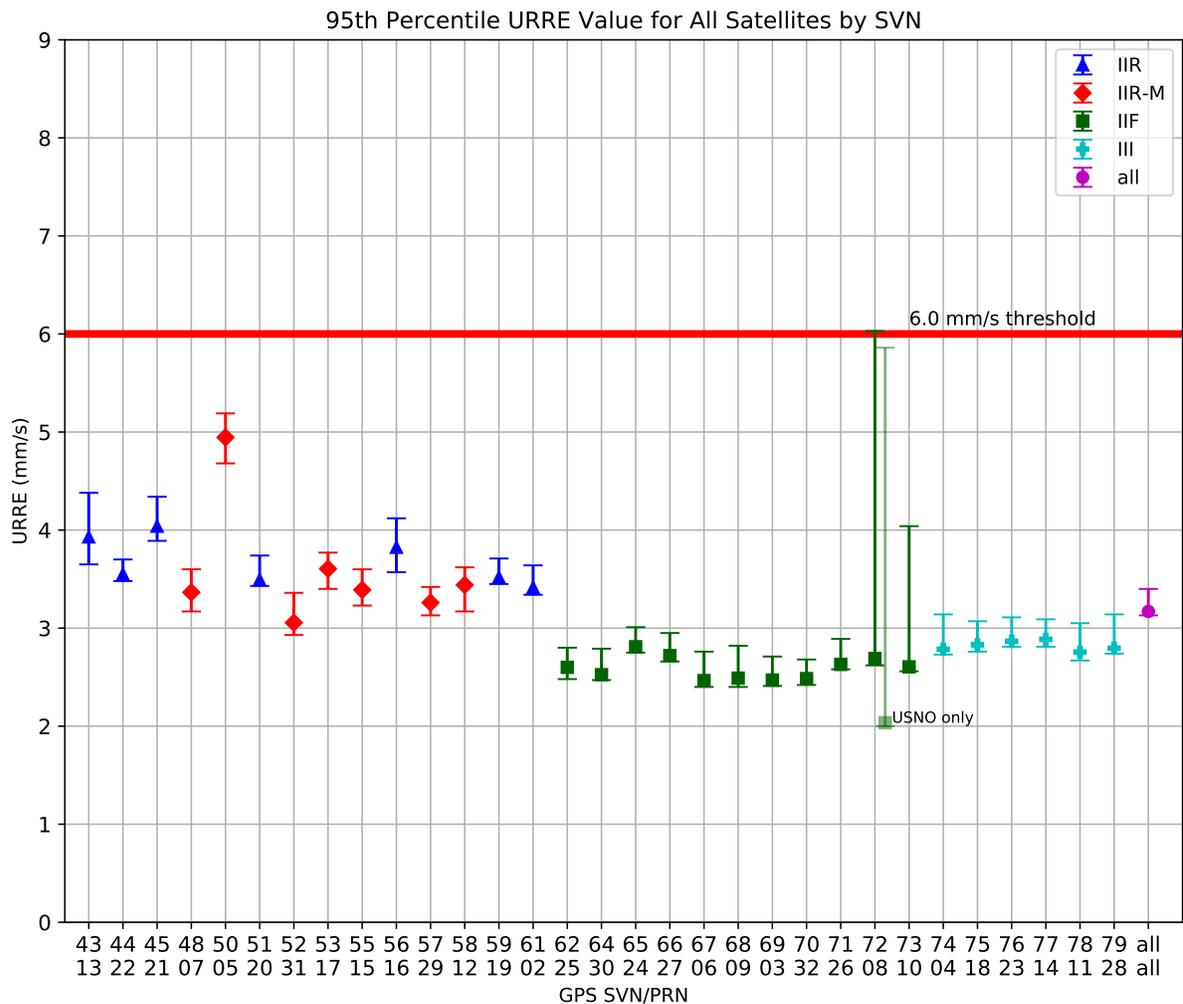


Figure 3.13: Range of the Monthly URRE 95th Percentile Values for All SVs

Notes: Each SVN with valid data is shown sequentially along the horizontal axis. The median value of the monthly 95th percentile URRE is displayed as a point on each of the vertical bars. The minimum and maximum of the monthly 95th percentile URRE for 2024 are shown by whiskers at the top and bottom of each vertical bar. Color distinguishes between the Block IIR, IIR-M, Block IIF, and GPS III SVs. The red horizontal line at 6.0 mm/s indicates the upper bound given by the SPS PS 2020 Section 3.4 performance metric. The marker for “all” represents the monthly 95th percentile values across all satellites. The marker for SVN 72/PRN 08 is duplicated to show both the range of values using all stations (unlabeled) and with only data from USNO considered (labeled “USNO only”). See Section 3.2.6 for details.

3.2.7 URAE Over All AOD

The SPS PS 2020 provides the following assertion for the user range acceleration error (URAE):

- “ ≤ 0.002 m/sec/sec 95% Global Statistic URAE over any 3-second interval during Normal Operations at Any AOD”

This is subject to the same general constraints from SPS PS 2020 Section 3.4 as the URE assertions.

The URAE is the time-derivative of the URRE. The URAE values were obtained by differencing the URRE values derived in support of the previous section. Table 3.6 contains the monthly 95th percentile values of the URAE based on the assumptions and constraints described above. For each SV, the worst value across the year is marked in red. Figure 3.14 provides a summary of these results for the entire constellation.

The values in Table 3.6 are all less than 2 mm/sec/sec except for the values associated with SVN 72/PRN 8 in January and February. As noted earlier, the values in the table are actually the user-equivalent range acceleration errors (UERAЕ) and include the noise of the receiver clock, as discussed in Section 3.2.6, which inflates the results. To explore this further, the URAE values were also computed using only data from the NGA monitor station at USNO. These results show 3% improvement over the values for SVN 72/PRN 8 in January and February, however these values are still 11-12% above the threshold. Depending on the relative weight assumed for the receiver clock noise versus the satellite clock noise, SVN 72/PRN 8 may or may not be within the threshold.

This requirement is considered to be met in 2024 for all SVs other than SVN 72/PRN 8. For SVN 72/PRN 8, the results are inconclusive.

Table 3.6: Monthly 95th Percentile Values of L1 P(Y) + L2 P(Y) SIS Instantaneous URAE for All SVs in mm/s/s

SVN	PRN	Block	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
43	13	IIR	1.72	1.81	1.74	1.68	1.70	1.68	1.72	1.72	1.83	1.78	1.68	1.70
44	22	IIR	1.62	1.59	1.56	1.58	1.59	1.56	1.57	1.59	1.66	1.68	1.60	1.65
45	21	IIR	1.59	1.61	1.63	1.64	1.64	1.62	1.64	1.66	1.79	1.76	1.63	1.66
48	7	IIR-M	1.36	1.41	1.36	1.38	1.42	1.35	1.35	1.37	1.46	1.48	1.38	1.35
50	5	IIR-M	1.64	1.70	1.62	1.61	1.64	1.62	1.54	1.61	1.72	1.71	1.57	1.62
51	20	IIR	1.54	1.55	1.51	1.52	1.54	1.51	1.51	1.52	1.68	1.66	1.54	1.58
52	31	IIR-M	1.26	1.31	1.27	1.27	1.30	1.26	1.25	1.26	1.39	1.36	1.21	1.23
53	17	IIR-M	1.40	1.39	1.29	1.30	1.36	1.34	1.34	1.34	1.44	1.43	1.30	1.36
55	15	IIR-M	1.38	1.50	1.39	1.33	1.37	1.37	1.35	1.36	1.48	1.42	1.32	1.34
56	16	IIR	1.58	1.59	1.59	1.64	1.64	1.58	1.58	1.59	1.75	1.75	1.64	1.64
57	29	IIR-M	1.29	1.33	1.32	1.28	1.31	1.29	1.27	1.28	1.40	1.36	1.23	1.26
58	12	IIR-M	1.33	1.46	1.34	1.28	1.34	1.29	1.26	1.26	1.38	1.38	1.26	1.28
59	19	IIR	1.54	1.60	1.51	1.51	1.52	1.50	1.50	1.53	1.62	1.60	1.51	1.54
61	2	IIR	1.50	1.51	1.51	1.53	1.53	1.52	1.54	1.56	1.65	1.66	1.53	1.54
62	25	IIF	1.33	1.40	1.34	1.28	1.34	1.30	1.26	1.28	1.38	1.36	1.23	1.25
64	30	IIF	1.27	1.29	1.23	1.25	1.29	1.25	1.24	1.24	1.37	1.34	1.26	1.23
65	24	IIF	1.42	1.52	1.42	1.37	1.45	1.40	1.38	1.39	1.48	1.47	1.36	1.36
66	27	IIF	–	1.38	1.32	1.32	1.38	1.36	1.33	1.34	1.44	1.41	1.31	1.32
67	6	IIF	1.23	1.27	1.20	1.20	1.27	1.23	1.21	1.23	1.36	1.32	1.24	1.22
68	9	IIF	1.26	1.29	1.23	1.24	1.29	1.26	1.24	1.25	1.40	1.37	1.19	1.21
69	3	IIF	1.27	1.30	1.21	1.22	1.28	1.25	1.21	1.22	1.34	1.34	1.23	1.21
70	32	IIF	1.25	1.28	1.23	1.23	1.28	1.24	1.22	1.23	1.32	1.30	1.19	1.22
71	26	IIF	1.33	1.37	1.29	1.30	1.36	1.34	1.31	1.31	1.43	1.37	1.28	1.30
72	8	IIF	2.31	2.30	1.32	1.32	1.38	1.36	1.32	1.33	1.46	1.40	1.30	1.30
72*	8*	IIF	2.25	2.23	1.17	1.16	1.26	1.23	1.14	1.14	1.15	1.14	1.15	1.14
73	10	IIF	1.69	1.50	1.28	1.28	1.34	1.30	1.28	1.29	1.35	1.37	1.26	1.28
74	4	III	1.42	1.43	1.43	1.46	1.44	1.42	1.43	1.44	1.61	1.58	1.40	1.43
75	18	III	1.42	1.43	1.44	1.45	1.46	1.43	1.44	1.46	1.55	1.57	1.44	1.44
76	23	III	1.45	1.45	1.45	1.47	1.49	1.46	1.48	1.49	1.59	1.57	1.45	1.47
77	14	III	1.49	1.45	1.44	1.47	1.47	1.44	1.47	1.48	1.56	1.58	1.49	1.52
78	11	III	1.39	1.42	1.41	1.41	1.43	1.40	1.40	1.43	1.56	1.55	1.43	1.43
79	28	III	1.43	1.45	1.45	1.46	1.46	1.42	1.43	1.45	1.61	1.59	1.43	1.45
All SVs			1.48	1.49	1.41	1.41	1.44	1.41	1.40	1.41	1.53	1.51	1.40	1.41

Notes: Values not present indicate that the satellite was not healthy throughout this period. Months during which an SV was healthy for less than 25 days are shown shaded. Months with the highest SIS instantaneous URAE for a given SV are colored red. The row at the bottom is the monthly 95th percentile values over all SVs. The * on the second row for SVN 72/PRN 08 indicates use of USNO data only. See Section 3.2.7 for more information.

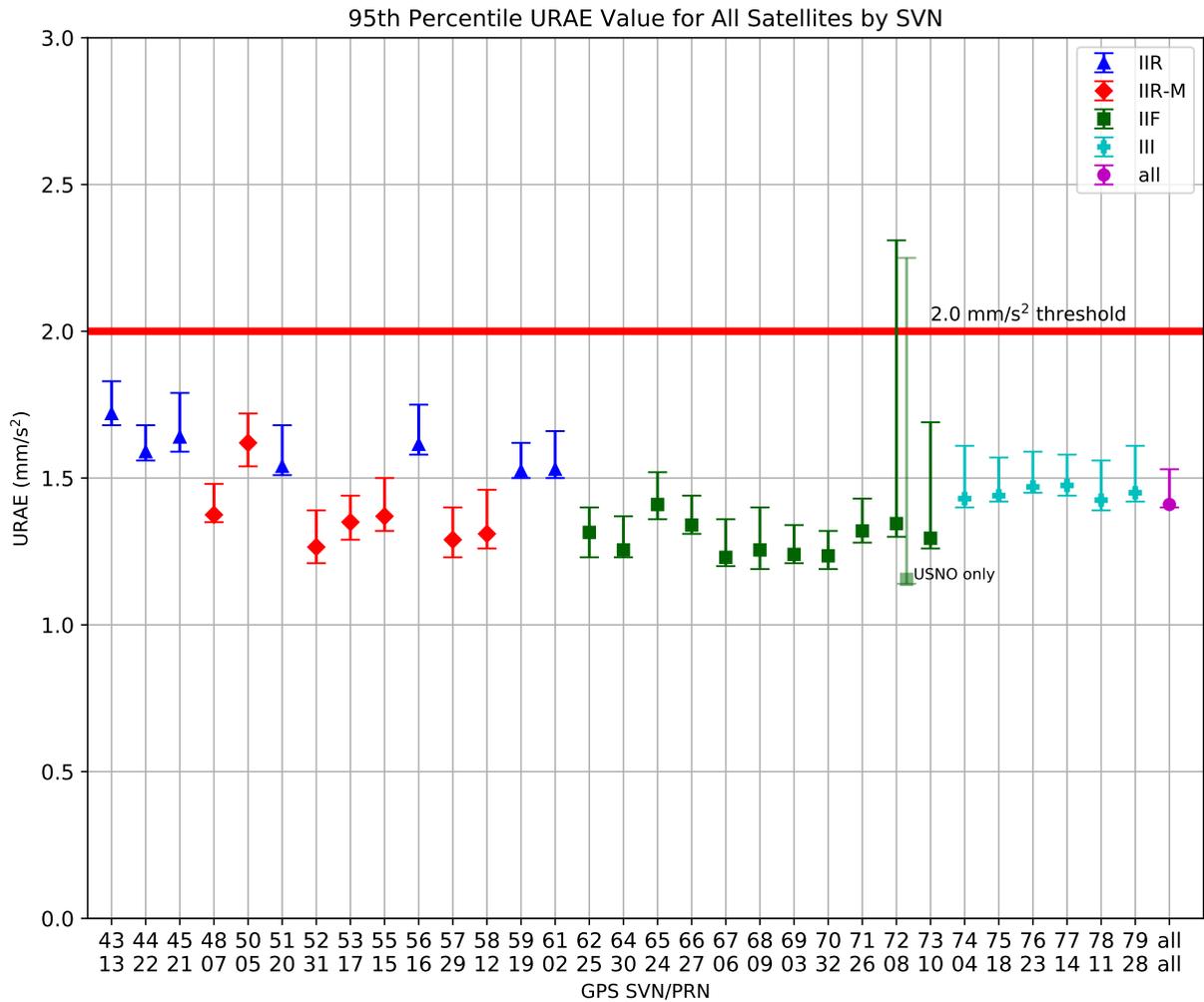


Figure 3.14: Range of the Monthly URAE 95th Percentile Values for All SVs

Notes: Each SVN with valid data is shown sequentially along the horizontal axis. The median value of the monthly 95th percentile URAE is displayed as a point on each of the vertical bars. The minimum and maximum of the monthly 95th percentile URAE for 2024 are shown by whiskers at the top and bottom of each vertical bar. Color distinguishes between the Block IIR, IIR-M, Block IIF, and GPS III SVs. The red horizontal line at 2.0 mm/s² indicates the upper bound given by the SPS PS 2020 Section 3.4 performance metric. The marker for “all” represents the monthly 95th percentile values across all satellites. The marker for SVN 72/PRN 08 is duplicated to show both the range of values using all stations (unlabeled) and with only data from USNO considered (labeled “USNO only”). See Section 3.2.7 for details.

3.2.8 UTC Offset Error

The SPS PS 2020 Section 3.4.4, Table 3.4-4 provides the following assertion regarding the Coordinated Universal Time (UTC) offset error (UTC OE) accuracy:

- “ ≤ 30 nsec 95% Global Statistic UTC OE during Normal Operations at Any AOD”

The conditions and constraints state that this assertion should be true for any healthy SPS SIS.

This assertion was evaluated by calculating the global statistic UTC OE at each 15 minute interval in the year. The GPS-UTC offset available to the user was calculated based on the GPS broadcast navigation message data available from the SV at that time. The GPS-UTC offset published information was provided by USNO daily GPS-UTC offset values. The USNO value for GPS-UTC at each evaluation epoch was derived from a multi-day spline fit to the daily published values.

The global statistic at each 15 minute epoch is determined by evaluating the UTC OE across the surface of the earth at each point on a 111 km \times 111 km grid. (This grid spacing corresponds to roughly 1° at the Equator.) At each grid point, the algorithm determines the set of SVs visible at or above the 5° minimum elevation angle that broadcast a healthy indication in the navigation message. For each of these SVs, the UTC offset information in the navigation message was compared to determine the data set that has an epoch time (t_{ot}) that is the latest of those that fall in the range $t_{current} \leq t_{ot} \leq t_{current} + 72$ hours. These data are used to form the UTC offset and UTC OE for that time-grid point. (The 72 hour value is derived from the 144 hour fit interval shown in IS-GPS-200 Table 20-XIII [2].)

The global statistics at each evaluation epoch are assembled into monthly data sets. The 95th percentile values are then selected from these sets.

The UTC offset parameters are contained in subframe 4, page 18 (data ID 56) of the GPS LNAV message transmitted on L1 C/A and in message type 33 of the GPS CNAV message transmitted on L2C and L5I. Typically, the values are identical across all three sources (within the precision provided). Because there are some differences between the LNAV and CNAV representations, the results were calculated for both LNAV and L2C CNAV. As a separate matter, we verified that the parameters transmitted on L2C CNAV and L5 CNAV for L5-capable SVs were identical. Therefore, the L5 results would be identical to the L2C results shown.

Figures 3.15 and 3.16 provide additional supporting information in the form of a time-history of global statistic UTC OE values at each 15 minute epoch for the year. Table 3.7 provides the results for each month of 2024. None of these values exceed the assertion of 30 nsec. Therefore, the assertion is verified for 2024.

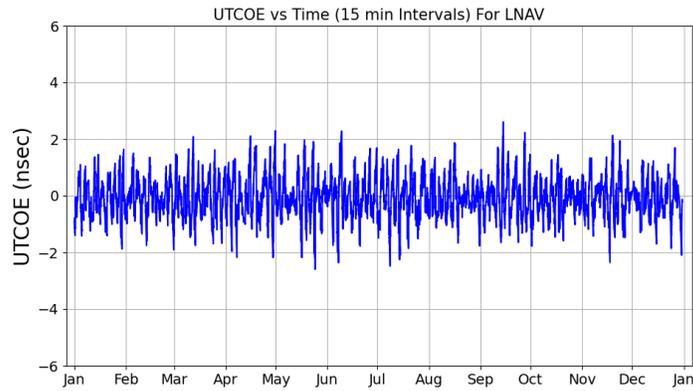


Figure 3.15: UTCOC LNAV Time Series for 2024

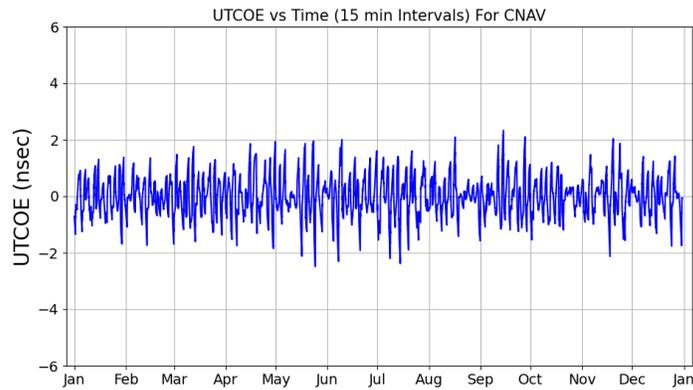


Figure 3.16: UTCOC CNAV Time Series for 2024

Table 3.7: 95th Percentile Global Statistic UTCOC for 2024

Month	95 th % Global Avg. UTCOC (nsec)	
	LNAV	CNAV
Jan.	1.29	1.17
Feb.	1.30	1.12
Mar.	1.40	1.29
Apr.	1.75	1.53
May	1.65	1.77
Jun.	1.67	1.59
Jul.	1.54	1.56
Aug.	1.25	1.22
Sep.	1.50	1.54
Oct.	1.15	1.03
Nov.	1.44	1.46
Dec.	1.30	1.26

3.3 SIS Integrity

3.3.1 URE Integrity

Under the heading of SIS Integrity, the SPS PS 2020 makes the following assertion in Section 3.5.1, Table 3.5-1:

- “ $\leq 1 \times 10^{-5}$ Probability Over Any Hour of the SPS SIS Instantaneous URE Exceeding the NTE Tolerance Without a Timely Alert”

The associated conditions and constraints include a limitation to a healthy SIS, a Not to Exceed (NTE) tolerance ± 4.42 times the upper bound on the user range accuracy (URA) currently broadcast by the satellite, a worst case for a delayed alert of 6 hours, and that the maximum SPS SIS instantaneous URE did not exceed the NTE tolerance at the start of the hour.

The reference to “a Timely Alert” in the assertion refers to any of a number of ways to issue an alert to the user through the GPS signal or navigation message. See SPS PS 2020 Section A.5.5 for a complete description.

Technically, there is no time range for this assertion in the SPS PS 2020. However, we assert on the one-year interval in parallel to the 2007 Precise Positioning Service (PPS) Performance Standard (PPS PS 2007). The PPS PS 2007 applies the following condition to the time period for the assertion:

- “Applies to any satellite marked as healthy in the NAV message measured over any one-year interval”

This assertion was verified using two methods:

- The instantaneous SIS URE values at the worst case location in view of each SV at each 5 minute interval were examined to determine the number of values that exceed ± 4.42 times the URA. (The worst location was selected from the set of instantaneous SIS URE values computed for each SV as described in Section 3.2.1.) The RMS UREs are also examined at a 30 second cadence near where the threshold may be exceeded.
- ORDs at each 30 second interval from the NGA MSN tracking stations were examined to determine the number of values that exceed ± 4.42 times the URA.

Two methods were used due to the fact that each method may result in false positives in rare cases. For example, the URE values may be incorrect near discontinuities in the PC&P (as described in Appendix C.2.5). Similarly, the ORD values may be incorrect due to receiver or reception issues. Therefore, all reported events are examined manually to determine whether an integrity fault actually occurred, and if so, the extent.

Screening the instantaneous SIS URE values and the ORD data revealed events for which the URE exceeded the NTE tolerance in 2024 across each signal. However, that does not mean that the assertion is met or unmet. Appendix A.6 contains additional information on these events.

The values computed for 2024 are shown below in Table 3.8.

Table 3.8: URE Integrity Statistics

Signal	Healthy SV Hours	Events	Probability
L1 C/A	270,313	1	3.70×10^{-6}
L1 C/A + L2C	209,271	4	1.91×10^{-5}
L1 C/A + L5Q	148,158	2	1.35×10^{-5}

The assertion is verified for 2024 for L1 C/A. The assertion was not met for L1 C/A + L2C. The assertion would be violated for L1 C/A + L5Q, however L5 is currently set unhealthy and is pre-operational.

3.3.2 UTCOE Integrity

The SPS PS 2020 provides the following assertion regarding UTCOE Integrity in Section 3.5.4:

- “ $\leq 1 \times 10^{-5}$ Probability Over Any Hour of the SPS SIS Instantaneous UTCOE Exceeding the NTE Tolerance Without A Timely Alert during Normal Operations”

The associated conditions and constraints include a limitation to a healthy SIS, and an NTE tolerance of ± 120 nsec, given that the maximum SPS SIS instantaneous UTCOE did not exceed the NTE tolerance at the start of the hour. The reference to “a Timely Alert” in the assertion refers to any of a number of ways to issue an alert. See SPS PS 2020 Section A.5.5 for a complete description.

This assertion was evaluated by calculating the UTC offset for the navigation message subframe 4 page 18 data broadcast by each SV transmitting a healthy indication in the navigation message at each 15 minute interval. As in Section 3.2.8, only UTC offset information with an epoch time (t_{ot}) that is in the range $t_{current} \leq t_{ot} \leq t_{current} + 72$ hours were considered valid. That offset was used to compute the corresponding UTCOE from published data obtained from USNO. If any UTCOE values exceed the NTE threshold of ± 120 nsec, they would be investigated to determine if they represented actual violations of the NTE threshold or were artifacts of data processing.

No values exceeding the NTE threshold were found in 2024. The value farthest from zero for the year was 2.61 nsec for LNAV in September and 2.49 nsec for CNAV in May (see Figures 3.15 and 3.16). Therefore, the assertion is verified for 2024.

3.3.3 Instantaneous P_{sat} and P_{const}

The SPS PS 2020 provides the following assertions regarding P_{sat} and P_{const} in Section 3.5.5:

- “ $\leq 1 \times 10^{-5}$ Fraction of Time When the SPS SIS Instantaneous URE Exceeds the NTE Tolerance Without a Timely Alert (P_{sat})”
- “ $\leq 1 \times 10^{-8}$ Fraction of Time When the SPS SIS Instantaneous URE from Two or More Satellites Exceeds the NTE Tolerance Due to a Common Cause Without a Timely Alert (P_{const})”

These are closely related to the SIS URE integrity assertion discussed in Section 3.3.1. Technically, there is no time range for this assertion in the SPS PS 2020. However, we assert on the one-year interval in parallel to the process in Section 3.3.1.

As noted in Section 3.3.1, there were events in which the SPS SIS instantaneous URE exceeded the NTE tolerance. See Appendix A.6 for additional information.

P_{sat} is computed as a fraction of time, across the constellation. The values computed for 2024 are shown below in Table 3.9.

Table 3.9: P_{sat} Statistics

Signal	Healthy SV Minutes	Event Duration (min)	Probability
L1 C/A	16,218,841	34.5	2.13×10^{-6}
L1 C/A + L2C	12,556,371	143.0	1.14×10^{-5}
L1 C/A + L5Q	8,889,508	28.0	3.15×10^{-6}

The P_{sat} assertion for 2024 was not met for L1 C/A + L2C. The assertion is verified for 2024 for L1 C/A and L1 C/A + L5Q.

Each event was limited to a single satellite, thus P_{const} is 0 for the year, which fulfills the assertion.

3.4 SIS Continuity

3.4.1 Unscheduled Failure Interruptions

The SIS continuity metric for single frequency L1 C/A-code is stated in SPS PS 2020 Table 3.6-1 as follows:

- “ ≥ 0.9998 Probability Over Any Hour of Not Losing the SPS SIS Availability from a Slot Due to Unscheduled Interruption”

The conditions and constraints note the following:

- The empirical estimate of the probability is calculated as an average over all slots in the 24-slot constellation, normalized annually.
- The SPS SIS is available from the slot at the start of the hour.

There is some ambiguity in this metric, which is stated in terms of “a slot,” while the associated conditions and constraints note that the assertion is an average over all slots. Therefore, both the per-slot and 24-slot constellation averages have been computed. As discussed below, while the per-slot values are interesting, the constellation average is the correct value to compare to the performance standard metric.

The notion of SIS continuity is slightly more complex for an expandable slot because multiple SVs are involved. Following SPS PS 2020 Section A.6.5, a loss of continuity is considered to occur when,

“The expandable slot is in the expanded configuration, and either one of the pair of satellites occupying the orbital locations defined in Table 3.2-2 for the slot loses continuity.”

Hence, the continuity of signal of the expanded slot will be determined by whether either SV loses continuity.

Three factors must be considered when looking at this metric:

1. Which SVs were assigned to which slots during the period of the evaluation.
2. When SVs were not transmitting, or were transmitting a PRN not available to users.
3. Which interruptions were scheduled vs. unscheduled.

The derivation of the SV/slot assignments is described in Appendix B.3.

For purposes of this report, interruptions were considered to have occurred if at least one of the following conditions is met:

1. One or more of the SVs assigned to the given slot are unhealthy as per SPS PS 2020 Section 2.3.2, which includes if the health bits in navigation message subframe 1 are set to anything other than all zeros.
2. If an appropriately distributed worldwide network of stations failed to collect any pseudorange data sets for a given SV for a given measurement interval. Failure to collect any data indicates that the satellite signal was removed from service (e.g., non-standard code or some other means).

The NGA MSN and IGS networks shown in Figure 1.1 provide continuous visibility from at least two stations with over 90% visibility from at least three stations. Therefore, if no data for a satellite are received for a specific time, it is highly likely that the satellite was not transmitting on the assigned PRN at that time. Receiver Independent Exchange format (RINEX) [8] observation files from these two networks were examined for each measurement interval (i.e., every 30 s) for each SV. If at least one receiver collected a pseudorange data set on LNAV with a signal-to-noise level of at least 25 dB-Hz on all frequencies and no loss-of-lock flags, the SV is considered trackable at that moment. This allows us to define an epoch-by-epoch availability for each satellite. For each slot, each hour in the year was examined. If an SV occupying the slot was not available at the start of the hour, the hour was not considered in the evaluation of the metric. If the slot was available at the start of the hour, the remaining data was examined to determine if an outage occurred during the hour.

The preceding criteria were applied to determine times and durations of interruptions. Subsequently, the Notice Advisories to Navstar Users (NANUs) effective in 2024 were reviewed to determine which of these interruptions could be considered scheduled interruptions, as defined in SPS PS 2020 Section 3.6. The scheduled interruptions were removed from consideration for purposes of assessing continuity of service. When a slot was available at the start of an hour but a scheduled interruption occurred during the hour, the hour was assessed based on whether data were available prior to the scheduled outage.

As defined in the ICD-GPS-240 [9], scheduled interruptions have a nominal notification time of 96 hours prior to the outage. Following the SPS PS 2020 Section 2.3.5, if the notification time for a scheduled interruption is less than 48 hours in advance of the interruption, the interruption will contribute to a loss of continuity.

The following NANU types are considered to represent (or modify) scheduled interruptions (assuming the 48-hour advance notice is met):

- FCSTDV - Forecast Delta-V
- FCSTMX - Forecast Maintenance
- FCSTRESCD - Forecast Rescheduled
- FCSTUUFN - Forecast Unusable Until Further Notice

We referenced the FCSTSUMM (Forecast Summary) NANU that occurs after the outage to confirm the actual beginning and ending time of the outage.

The results of the assessment of SIS continuity are summarized in Table 3.10. The metric is averaged over the constellation; therefore, the value in the bottom row (labeled “All Slots”) must be greater than 0.9998 in order to meet the assertion.

Table 3.10: Probability Over Any Hour of Not Losing L1 C/A Availability Due to Un-scheduled Interruption for 2024

Plane-Slot	Count of Hours with the SPS SIS available at the start of the hour ^b	Count of Hours with Unscheduled Interruption ^c	Fraction of Hours in Which Availability was Maintained
A1	8779	0	1.000000
A2 ^a	8777	0	1.000000
A3	8779	0	1.000000
A4	8512	1	0.999883
B1 ^a	8778	0	1.000000
B2	8778	0	1.000000
B3	8784	0	1.000000
B4	8779	0	1.000000
C1	8778	0	1.000000
C2	7997	0	1.000000
C3	8639	0	1.000000
C4 ^a	8705	2	0.999770
D1	8777	0	1.000000
D2 ^a	8778	0	1.000000
D3	8778	0	1.000000
D4	8756	1	0.999886
E1	8779	0	1.000000
E2	8624	0	1.000000
E3 ^a	8773	0	1.000000
E4	8779	0	1.000000
F1	8784	0	1.000000
F2 ^a	8779	1	0.999886
F3	8778	0	1.000000
F4	8778	0	1.000000
All Slots	209248	5	0.999976

^aWhen any of A2, B1, C4, D2, E3, and F2 are configured as expandable slots, both slot locations must be occupied by an available satellite for the slot to be counted as available.

^bThere were 8,784 hours in the evaluation period.

^cNumber of hours in which SPS SIS was available at the start of the hour and during the hour either (1) an SV transmitted navigation message with subframe 1 health bits set to anything other than all zeroes without a scheduled outage, or (2) signal lost without a scheduled outage.

To put this in perspective, there are 8,760 hours in a year (8,784 for a leap year). The required probability of not losing SPS SIS availability over an hour is calculated as an average over all slots in the 24-slot constellation. The maximum number of hours that can experience unscheduled interruptions over the year is given by $8,760 \times (1 - 0.9998) \times 24 = 42$ hours. This is less than two unscheduled interruptions per SV per year but allows for the possibility that some SVs may have no unscheduled interruptions while others may have more than one.

Returning to Table 3.10, across the slots in the constellation, the total number of hours lost was 5. This is smaller than the maximum number of hours of unscheduled interruptions (42) available to meet the metric and leads to the empirical value for the fraction of hours in which SPS SIS continuity was maintained of 0.999976. Therefore, this assertion is considered fulfilled in 2024.

3.4.2 Status and Problem Reporting Standards

3.4.2.1 Scheduled Events

The SPS PS 2020 makes the following assertion in Section 3.6.3 regarding notification of scheduled events affecting service to the Coast Guard and the Federal Aviation Administration (FAA):

- *“Appropriate NANU issued to the Coast Guard and the FAA at least 48 hours prior to the event for 95% of the events”*

While beyond the assertion in the performance standards, ICD-GPS-240 [9] states a threshold of no less than 48 hours and a nominal notification time of 96 hours prior to outage start.

This metric was evaluated by comparing the NANU periods to outages observed in the data. In general, scheduled events are described in a pair of NANUs. The first NANU is a forecast of when the outage will occur. The second NANU is provided after the outage and summarizes the actual start and end times of the outage. (This is described in ICD-GPS-240 Section 10.1.1).

Table 3.11 summarizes the pairs found for 2024. The two leftmost columns provide the SVN/PRN of the subject SV. The next three columns specify the NANU #, type, and release time of the forecast NANU. These are followed by three columns that specify the NANU #, the release date/time of the FCSTSUMM NANU provided after the outage, and the date/time of the beginning of the outage. The final column is the time difference between the time the forecast NANU was released and the beginning of the actual outage (in hours). This represents the length of time between the release of the forecast NANU and the actual start of the outage. The average notice time in 2024 was over 140 hours.

One satellite was decommissioned and one satellite was launched in 2024. Tables 3.12 and 3.13 provide the details on how this was represented in the NANUs.

To meet the assertion in the performance standard, at least 95% of the values in the rightmost column of Table 3.11 should be greater than 48.0. For 2024, all events had a notice time greater than 48 hours. Therefore, this assertion is satisfied.

Table 3.11: Scheduled Events Covered in NANUs for 2024

SVN	PRN	Forecast NANU			Summary NANU (FCSTSUMM)			Notice (hrs)
		NANU #	TYPE	Release Time	NANU #	Release Time	Start Of Outage	
69	03	2023075	FCSTDV	29 Dec 1649Z	2024001	05 Jan 1232Z	05 Jan 0748Z	158.98
65	24	2024002	FCSTDV	07 Jan 1844Z	2024003	11 Jan 1648Z	11 Jan 1148Z	89.07
50	05	2024004	FCSTDV	18 Jan 1622Z	2024005	26 Jan 0743Z	26 Jan 0218Z	177.93
61	02	2024006	FCSTDV	01 Feb 1746Z	2024009	09 Feb 0804Z	09 Feb 0231Z	176.75
73	10	2024008	FCSTMX	06 Feb 2254Z	2024011	16 Feb 1424Z	09 Feb 1642Z	65.80
72	08	2024010	FCSTMX	15 Feb 1608Z	2024012	27 Feb 2218Z	21 Feb 2059Z	148.85
74	04	2024013	FCSTDV	29 Feb 2228Z	2024015	08 Mar 1330Z	08 Mar 0750Z	177.37
57	29	2024016	FCSTMX	13 Mar 1555Z	2024017	20 Mar 2106Z	20 Mar 1936Z	171.68
53	17	2024018	FCSTMX	27 Mar 1441Z	2024019	05 Apr 1457Z	03 Apr 1511Z	168.50
62	25	2024024	FCSTRESCD	17 May 0428Z	2024026	22 May 1411Z	22 May 0850Z	124.37
56	16	2024027	FCSTDV	23 May 2148Z	2024029	31 May 1135Z	31 May 0540Z	175.87
51	20	2024032	FCSTRESCD	13 Jun 1436Z	2024033	18 Jun 2018Z	18 Jun 1449Z	120.22
76	23	2024034	FCSTDV	21 Jun 2102Z	2024036	27 Jun 2354Z	27 Jun 1837Z	141.58
43	13	2024037	FCSTDV	01 Aug 1905Z	2024038	08 Aug 1831Z	08 Aug 1329Z	162.40
57	29	2024039	FCSTDV	09 Aug 1934Z	2024040	16 Aug 0204Z	15 Aug 2021Z	144.78
75	18	2024041	FCSTDV	09 Sep 1922Z	2024042	13 Sep 0929Z	13 Sep 0324Z	80.03
53	17	2024043	FCSTDV	13 Sep 1907Z	2024044	19 Sep 0323Z	18 Sep 2045Z	121.63
52	31	2024045	FCSTDV	19 Sep 2046Z	2024046	27 Sep 1144Z	27 Sep 0445Z	175.98
78	11	2024047	FCSTDV	27 Sep 1630Z	2024048	04 Oct 0629Z	03 Oct 2308Z	150.63
64	30	2024050	FCSTRESCD	09 Oct 1845Z	2024051	16 Oct 0433Z	15 Oct 2321Z	148.60
59	19	2024052	FCSTDV	10 Nov 0117Z	2024053	15 Nov 0837Z	15 Nov 0232Z	121.25
58	12	2024054	FCSTDV	18 Nov 1617Z	2024056	21 Nov 0354Z	20 Nov 2213Z	53.93
48	07	2024059	FCSTDV	29 Nov 1810Z	2024061	06 Dec 1024Z	06 Dec 0455Z	154.75
45	21	2024060	FCSTMX	03 Dec 1836Z	2024064	13 Dec 1916Z	11 Dec 1101Z	184.42
68	09	2024066	FCSTDV	18 Dec 1802Z	2024069	23 Dec 2117Z	23 Dec 1534Z	117.53
Average Notice Period								140.52

Table 3.12: Decommissioning Events Covered in NANUs for 2024

SVN	PRN	FCSTUUFN/UNUSUFN NANU		DECOM NANU			Notice (hrs)
		NANU #	Release Time	NANU #	Release Time	End of Unusable Period	
44	22	2024062	12 Dec 1936Z	2024067	19 Dec 2248Z	16 Dec 1516Z	91.67
Average Notice Period							91.67

Table 3.13: Usable Events Covered in NANUs for 2024

SVN	PRN	LAUNCH/GENERAL NANU		USABINIT NANU	
		NANU #	Launch Time	NANU #	Start Time
80	1	2024068	17 Dec 0052Z	-	-

3.4.2.2 Unscheduled Outages

The SPS PS 2020 provides the following assertion in Section 3.6.3 regarding notification of unscheduled outages or problems affecting service:

- “Appropriate NANU issued to the Coast Guard and the FAA as soon as possible after the event”

The ICD-GPS-240 states that the nominal notification time is 15 minutes after the start of an outage with a threshold of less than 1 hour.

This metric was evaluated by examining the NANUs provided throughout the year and comparing the NANU periods to outages observed in the data. Unscheduled events may be covered by either a single NANU or a pair of NANUs. In the case of a brief outage, a NANU with type UNUNOREF (unusable with no reference) is provided to detail the period of the outage. In the case of longer outages, a UNUSUFN (unusable until further notice) is provided to inform users of an ongoing outage or problem. This is followed by a NANU with type UNUSABLE after the outage is resolved. (This is described in detail in ICD-GPS-240 Section 10.1.2).

Table 3.14 provides a list of the unscheduled outages found in the NANU information for 2024. The two leftmost columns provide the SVN/PRN of the subject SV. The third column provides the plane-slot of the SV to assist in relating these events to the information in Table 3.10. The next two columns provide the NANU # and release date/time of the UNUSUFN NANU. These are followed by three columns that specify the NANU #, the release date/time of the UNUSABLE NANU provided after the outage, and the date/time of the beginning of the outage. The final column is the time difference between the outage start time and the UNUSUFN NANU release time (in hours). Values in the final column are shown in red if they have a lag time of greater than 60 minutes (1 hour).

Because the performance standard states only “as soon as possible after the event,” there is no threshold check to be performed. However, the data are provided for information. With respect to the notification times provided in ICD-GPS-240, the threshold time was not met for one of the events listed in Table 3.14.

Table 3.14: Unscheduled Events Covered in NANUs for 2024

SVN	PRN	Plane-Slot	UNUSUFN NANU		UNUSABLE/UNUNOREF NANU			Lag Time (minutes)
			NANU #	Release Time	NANU #	Release Time	Start Of Event	
66	27	C2	2023076	30 Dec 1115Z	2024007	02 Feb 1853Z	30 Dec 1107Z	8.00
53	17	C4F	–	–	2024022	17 May 0050Z	17 May 0011Z	39.00
53	17	C4F	2024023 ^a	17 May 0110Z	2024025	17 May 2006Z	17 May 0116Z	-6.00
48	07	A4	2024028	25 May 1627Z	2024030	05 Jun 1825Z	25 May 1620Z	7.00
43	13	F2F	–	–	2024035	24 Jun 1950Z	24 Jun 0230Z	1040.00
67	06	D4	2024057	26 Nov 1712Z	2024058	27 Nov 2032Z	26 Nov 1658Z	14.00
Average Lag Time								221.60

^aNANU release time is prior to event start time. Event not included in average lag time.

3.5 SIS Availability

3.5.1 Per-Slot Availability

The SPS PS 2020 makes the following assertions in Section 3.7.1:

- “ ≥ 0.957 Probability that a Slot in the Baseline 24-Slot Configuration will be Occupied by a Satellite Broadcasting a Healthy SF CA-code SPS SIS”
- “ ≥ 0.957 Probability that a Slot in the Expanded Configuration will be Occupied by a Pair of Satellites Each Broadcasting a Healthy SF CA-code SPS SIS”

The constraints include the note that this is to be calculated as an average over all slots in the 24-slot constellation, normalized annually.

The derivation of the SV/slot assignments is described in Appendix B.3.

This metric was verified by examining the status of each SV in the 24-slot configuration (or pair of SVs in an expandable slot) at every 30 s interval throughout the year. The health status was determined from the subframe 1 health bits of the ephemeris being broadcast at the time of interest. In addition, data from both the MSN and the IGS networks were examined to verify that the SV was broadcasting a trackable signal at the time. The results are summarized in Table 3.15. The metric is averaged over the constellation; therefore, the value in the bottom row (labeled “All Slots”) must be greater than 0.957 in order for the assertion to be met.

Slot C2 had a lower availability than the other slots due to the outage on SVN 66/PRN 27 from the start of the year until 02 February 2024 (NANU 2024007).

Regardless of the individual slot availabilities, the average availability for the constellation was 0.993, which is above the threshold of 0.957. Therefore, the assertion being evaluated in this section was met.

Table 3.15: Per-Slot L1 C/A Availability for 2024

Plane-Slot	# Missing Epochs ^b	Availability
A1	575	0.999455
A2 ^a	783	0.999257
A3	618	0.999414
A4	32571	0.969100
B1 ^a	683	0.999352
B2	627	0.999405
B3	0	1.000000
B4	633	0.999399
C1	794	0.999247
C2	94428	0.910417
C3	17421	0.983473
C4 ^a	9492	0.990995
D1	868	0.999177
D2 ^a	662	0.999372
D3	708	0.999328
D4	3343	0.996829
E1	563	0.999466
E2	19154	0.981829
E3 ^a	1289	0.998777
E4	623	0.999409
F1	0	1.000000
F2 ^a	592	0.999438
F3	680	0.999355
F4	716	0.999321
All Slots	187823	0.992576

^aWhen any of A2, B1, C4, D2, E3, and F2 are configured as expandable slots, both slot locations must be occupied by an available satellite for the slot to be counted as available.

^bFor each slot, there were 1,054,080 total 30 s epochs in the evaluation period.

3.5.2 Constellation Availability

The SPS PS 2020 makes the following assertions in Section 3.7.2:

- “ ≥ 0.98 Probability that at least 21 Slots out of the 24 Slots will be Occupied Either by a Satellite Broadcasting a Healthy SF CA-code SPS SIS in the Baseline 24-Slot Configuration or by a Pair of Satellites Each Broadcasting a Healthy SPS SIS in the Expanded Slot Configuration”
- “ ≥ 0.99999 Probability that at least 20 Slots out of the 24 Slots will be Occupied Either by a Satellite Broadcasting a Healthy SF CA-code SPS SIS in the Baseline 24-Slot Configuration or by a Pair of Satellites Each Broadcasting a Healthy SF CA-code SPS SIS in the Expanded Slot Configuration”

To evaluate this metric, the subframe 1 health condition and the availability of signal were evaluated for each SV every 30 s for all of 2024. For non-expanded baseline slots, if an SV qualified as being in the slot and was transmitting a healthy signal, the slot was counted as occupied. For expanded slots, the slot was counted as occupied if two SVs were transmitting healthy signals in the slot, with one in each of the two portions of the expanded slot. Each 30 s epoch in 2024 had at least 21 slots occupied by a satellite broadcasting a healthy CA-code signal. Thus, both requirements are satisfied.

While this satisfies the metric, it does not provide much information on exactly how many SVs are typically healthy. To address this, at each 30 s interval, the number of SVs broadcasting a healthy SIS was counted. This was done for both healthy SVs occupying slots and for all healthy SVs. The daily averages as a function of time are shown in Figure 3.17.

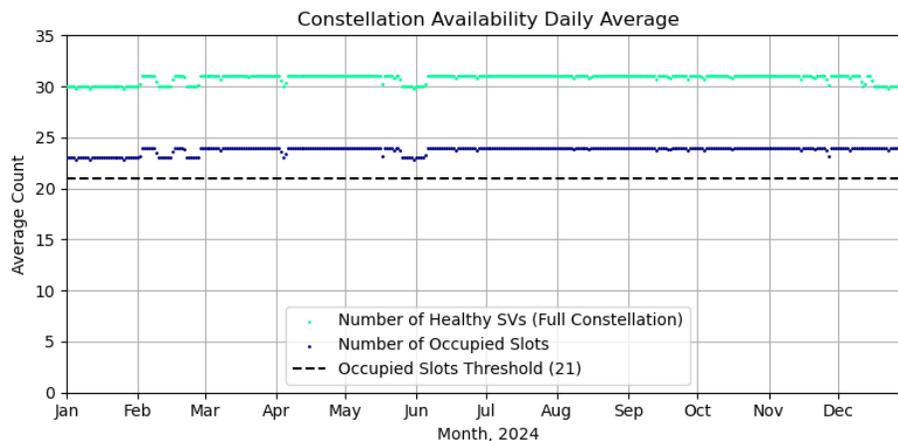


Figure 3.17: Daily Average Number of Healthy Satellites

3.5.3 Operational Satellite Counts

Table 3.7-3 of the SPS PS 2020 states:

- *“ ≥ 0.95 Probability that the Constellation will Have at least 24 Operational Satellites Regardless of Whether Those Operational Satellites are Located in Slots or Not”*

Under “Conditions and Constraints” the term Operational is defined as

“any satellite which appears in the transmitted navigation message almanac... regardless of whether that satellite is currently broadcasting a healthy SPS SIS or not or whether the broadcast SPS SIS also satisfies the other performance standards in this SPS PS 2020 or not.”

Given the information presented in Sections 3.5.1 and 3.5.2, we conclude that at least 24 SVs were operational 100% of the time for 2024, thus meeting the assertion.

To evaluate this more explicitly, the almanac status was examined directly. Using the published almanacs, the daily count of operational satellites was determined to be 31 for all days in 2024.

3.6 Position/Velocity/Time Domain Standards

3.6.1 Evaluation of DOP Assertions

Dilution of precision (DOP) measures the geometric diversity of a set of observations. That is to say, the diversity of the lines of sight from a user to the observed usable SVs. There are a variety of types of DOP, including:

- position dilution of precision (PDOP),
- geometric dilution of precision (GDOP),
- horizontal dilution of precision (HDOP),
- vertical dilution of precision (VDOP), and
- time dilution of precision (TDOP).

Accurate position and time solutions require two components: a sufficient number of accurate signals, and an acceptable geometric diversity of those signals. The former requirement is addressed by the URE assertions in Section 3.4 of the SPS PS 2020, and the latter is addressed by the PDOP assertions in Section 3.8.1 of the SPS PS 2020.

Section 3.6.1.1 provides the evaluation of the PDOP assertions stated in SPS PS 2020. Appendix A.7 provides additional supporting information beyond the stated assertions and includes results specific to the various types of DOP to better explain how well the constellation meets the assertions.

3.6.1.1 PDOP Availability

The PDOP availability standards are stated in Table 3.8-1 of the SPS PS 2020 as follows:

- “ $\geq 98\%$ global PDOP of 6 or less”
- “ $\geq 88\%$ worst site PDOP of 6 or less”

Based on the definition of a representative receiver contained in SPS PS 2020 Section 3.8, a 5° minimum elevation angle is used for this evaluation.

These assertions were verified empirically throughout 2024 using a uniformly-spaced grid, containing N_{grid} points, to represent the terrestrial service volume at zero altitude, and an archive of the broadcast ephemerides transmitted by the SVs throughout the year. All healthy, transmitting SVs were considered. The grid was $111 \text{ km} \times 111 \text{ km}$ (roughly $1^\circ \times 1^\circ$ at the Equator). The time started at 0000Z each day and stepped through the entire day at one minute intervals (1,440 points/day, defined as $1 \leq N_t \leq 1440$). The overall process followed is similar to that defined in Section 5.4.6 of the GPS Civil Monitoring Performance Specification (CMPS) [10].

The PDOP values were formed using the traditional PDOP algorithm [11], without regard for the effect of terrain. The coordinates of the grid locations provided the ground positions at which the PDOP was computed. The position of each SV was computed from the broadcast ephemeris available to a theoretical receiver at that grid point at the time of interest. The only filtering performed was the exclusion of any unhealthy SVs (those with subframe 1 health bits set to other than all zeroes). The results of each calculation were tested with respect to the threshold of $PDOP \leq 6$. At each point in time, if the condition was violated, a bad PDOP counter associated with the particular grid point, b_i for $1 \leq i \leq N_{grid}$, was incremented. Once the summation over time is complete, b_i represents the number of bad PDOP flags observed at grid point i throughout the 24-hour period of interest.

At least four SVs must be available to a receiver for a valid PDOP computation. This condition was fulfilled for all grid points at all times in 2024.

Once the PDOPs had been computed across all grid points, for each of the 1,440 time increments during the day, the percentage of time $PDOP \leq 6$ for the day was computed using the formula:

$$(\%PDOP \leq 6) = 100 \left(1 - \frac{\sum_{i=1}^{N_{grid}} b_i}{N_{grid} N_t} \right)$$

The worst site for a given day was identified from the same set of counters by finding the site with the maximum bad count: $b_{max} = \max_i(b_i)$. The ratio of b_{max} to N_t is an estimate of the fraction of time the worst site PDOP exceeds the threshold. This value was averaged over the year, and the percentage of time $PDOP \leq 6$ was computed.

Table 3.16 summarizes the results of this analysis. The second column provides the values for the assertions. The third column is provided to verify that no single-day value actually dropped below the goal. From this table we conclude that the PDOP availability metrics are met for 2024.

Table 3.16: Summary of PDOP Availability

Metric	Average daily % over 2024	Minimum daily % over 2024
$\geq 98\%$ Global Average $PDOP \leq 6$	100.000	99.999
$\geq 88\%$ Worst site $PDOP \leq 6$	99.930	98.264

In addition to verifying the assertion, further DOP analyses were conducted which go beyond the assertion and speak to system performance on a more granular basis. The remainder of this chapter describes those analyses and results. For more additional DOP analysis, see Appendix A.7.

The day-to-day variations in PDOP were also examined in addition to the statistics presented above. Figure 3.18 provides a time history of PDOP metrics considering all satellites for 2024. Three metrics are plotted:

- Light Blue: Average PDOP at Worst Site ($\langle PDOP_{worst\ site} \rangle$)
- Blue: Average Worst Site PDOP ($\langle PDOP \rangle_{worst\ site}$)
- Green: Daily Global Average PDOP ($\langle PDOP \rangle$)

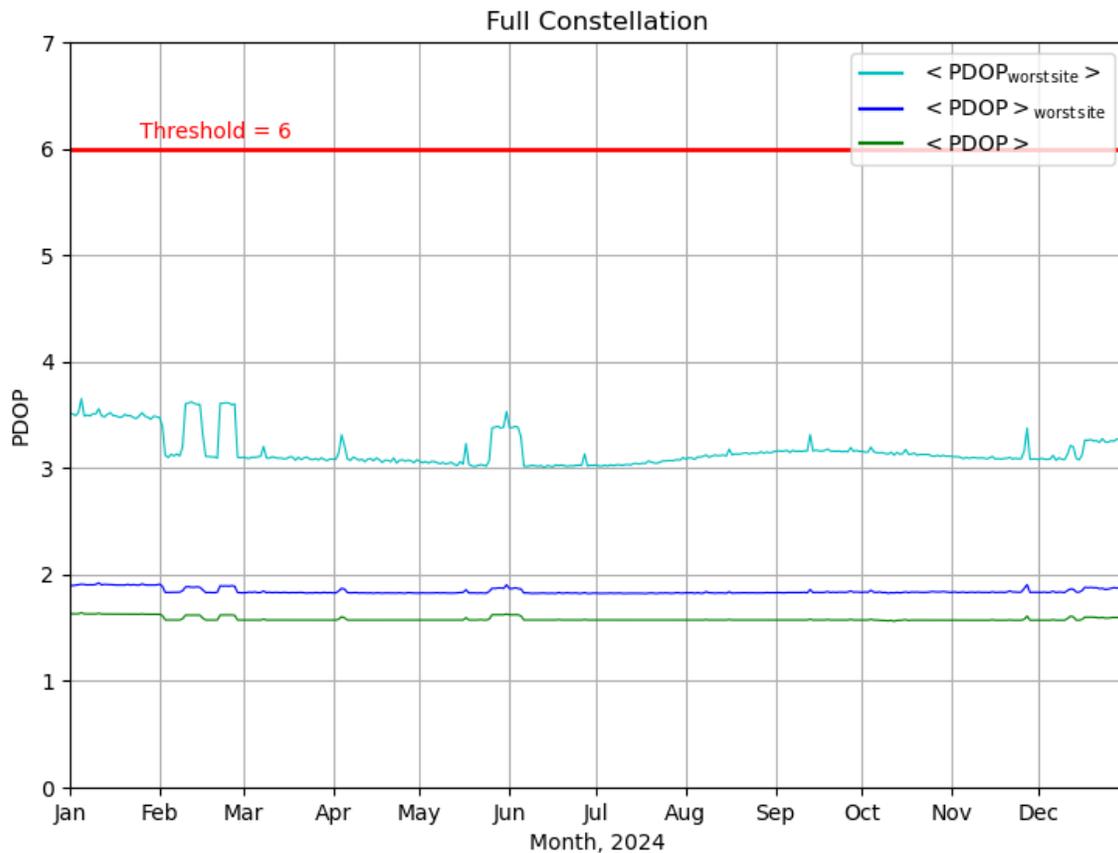


Figure 3.18: Daily PDOP Metrics Using All SVs for 2024

3.6.2 Position Service Availability

The positioning and timing availability standards are stated in Table 3.8-2 of the SPS PS 2020 as follows:

- “ $\geq 99\%$ Horizontal Service Availability, average location”
- “ $\geq 99\%$ Vertical Service Availability, average location”
- “ $\geq 90\%$ Horizontal Service Availability, worst-case location”
- “ $\geq 90\%$ Vertical Service Availability, worst-case location”

The conditions and constraints note that the percentages in the assertions are associated with the availability of a horizontal accuracy of 15 m (95th%, SIS only) and a vertical accuracy of 33 m (95th%, SIS only).

These values are derived as described in the sentence preceding SPS PS 2020 Table 3.8-2:

“The commitments for maintaining PDOP (Table 3.8-1) and SPS SIS URE accuracy (Table 3.4-1) result in support for position service availability standards as presented in Table 3.8-2.”

Because the commitments for PDOP and constellation SPS SIS URE have been met, this assertion in the SPS PS 2020 implies that the position and timing availability standards have also been fulfilled. A direct assessment of these metrics was not undertaken.

3.6.3 Position/Velocity Accuracy

The positioning accuracy standards are stated in Table 3.8-3 of the SPS PS 2020 as follows:

- “ ≤ 8 m 95% Horizontal Error, Global Average Position Domain Accuracy”
- “ ≤ 13 m 95% Vertical Error, Global Average Position Domain Accuracy”
- “ ≤ 15 m 95% Horizontal Error, Worst Site Position Domain Accuracy”
- “ ≤ 33 m 95% Vertical Error, Worst Site Position Domain Accuracy”
- “ ≤ 0.2 m/s 95% velocity error, any axis, Global Average Velocity Accuracy”

These values are derived as described in the sentence preceding SPS PS 2020 Table 3.8-3:

“The commitments for maintaining PDOP (Table 3.8-1), SPS SIS URE accuracy (Table 3.4-1), and SPS SIS URRE accuracy (Table 3.4-2), result in support for position/velocity/time accuracy standards as presented in Table 3.8-3.”

Because the commitments for PDOP, constellation SPS SIS URE, and constellation SPS SIS URRE have been met, the position, velocity, and timing accuracy standards have also been fulfilled.

While this verifies the assertion has been fulfilled, it is useful to corroborate that finding through examination of empirical results. We do this by evaluating position solutions (generated via the process described in Appendix C.5) for a set of continuously operating stations from both the NGA and IGS networks (see Figure 1.1). The process uses both a receiver autonomous integrity monitoring (RAIM) approach and a simplistic approach with no data editing. We conducted the elevation angle processing with a 5° minimum elevation angle in agreement with the standard.

Once the solutions are computed, two sets of statistics were developed for each approach, yielding 4 sets of results. The first set is a set of daily average position errors across all stations. In the second set, the worst site is determined on a day-to-day basis and the worst site 95th percentile position errors are computed.

There are a number of differences between the two station sets. The NGA station set is more homogeneous in that the same receiver model is used throughout the data processed for this analysis and a single organization prepared all the data sets using a single set of algorithms. By contrast, the IGS data sets come from a variety of receivers and were prepared and submitted by a variety of organizations.

These are empirical results and should not be construed to represent proof that the metrics presented in the standard have been met. Instead, they are presented as a means of corroboration that the standards have been met through the fulfillment of the more basic commitments of PDOP and SPS SIS URE.

3.6.3.1 Results for Daily Average

Using the approach outlined above, position solutions were computed at each 30 s interval for data from both the NGA and IGS stations. In the nominal case in which all stations are operating for a complete day, this yields 2,880 solutions per station per day. Reference positions for the IGS stations were taken from the weekly Station Independent Exchange format (SINEX) files. Reference locations for the NGA stations were taken from station locations defined as part of the latest World Geodetic System (WGS) 84 reference frame [12] with corrections for station velocities applied.

Residuals between estimated locations and the reference locations were computed in the form of North, East, and Up components in meters. The horizontal residual was computed from the root sum square (RSS) of the North and East components, and the vertical residual was computed from the absolute value of the Up component. As a result, the residuals will have non-zero mean values. The statistics on the residuals were compiled across all stations in a set for a given day. Figures 3.19 – 3.22 show the daily average for the horizontal and vertical residuals corresponding to the four cases.

The statistics associated with the processing are provided in Table 3.17. The table contains the mean, median, maximum, and standard deviation of the daily values across 2024. The results are organized in this fashion to facilitate comparison of the same quantity across the various processing options. The results are expressed to the centimeter level of precision. This choice of precision is based on the fact that the reference station positions are known only at the few-centimeter level.

The following observations regarding the quality of the daily average position solutions may be drawn from the charts and the supporting statistics in Table 3.17:

- The means and medians of the position residuals are nearly identical for both the NGA and IGS data sets, suggesting that if there are any 30 s position residual outliers, they are few in number and not too large.
- For both data sets, the standard deviation for the pseudorange solutions is higher than for the RAIM solutions. This indicates the importance of data editing in position processing.
- Vertical position residuals are higher than horizontal position residuals for both data sets.

Table 3.17: Daily Average Position Errors for 2024

Statistic	Data Editing	Horizontal		Vertical	
		IGS	NGA	IGS	NGA
Mean (m)	RAIM	1.07	0.97	1.71	1.33
	None	1.08	0.98	1.74	1.34
Median (m)	RAIM	1.06	0.96	1.70	1.31
	None	1.07	0.96	1.72	1.32
Maximum (m)	RAIM	1.38	1.47	2.15	1.92
	None	2.08	2.16	4.95	2.98
Std. Dev. (m)	RAIM	0.04	0.05	0.06	0.06
	None	0.08	0.09	0.20	0.12

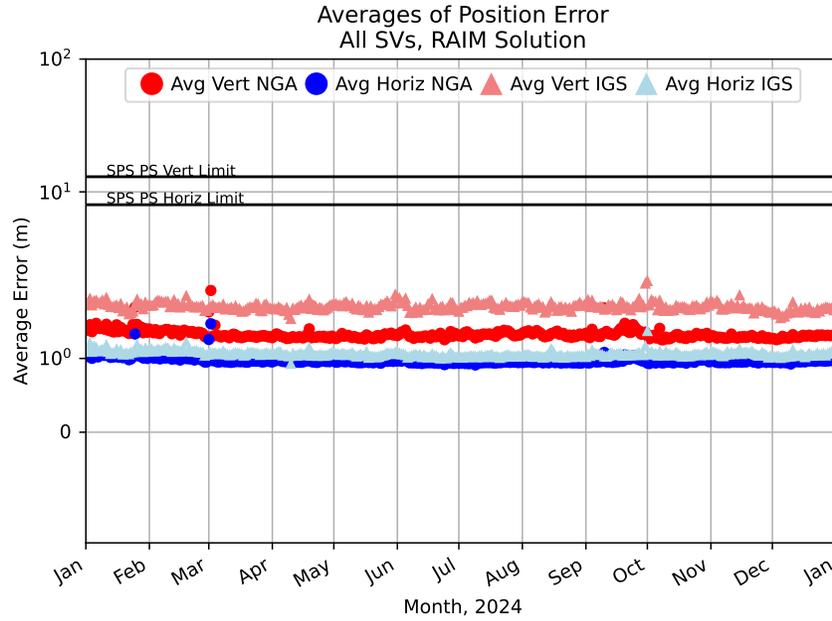


Figure 3.19: Daily Averaged Position Residuals Computed Using a RAIM Solution

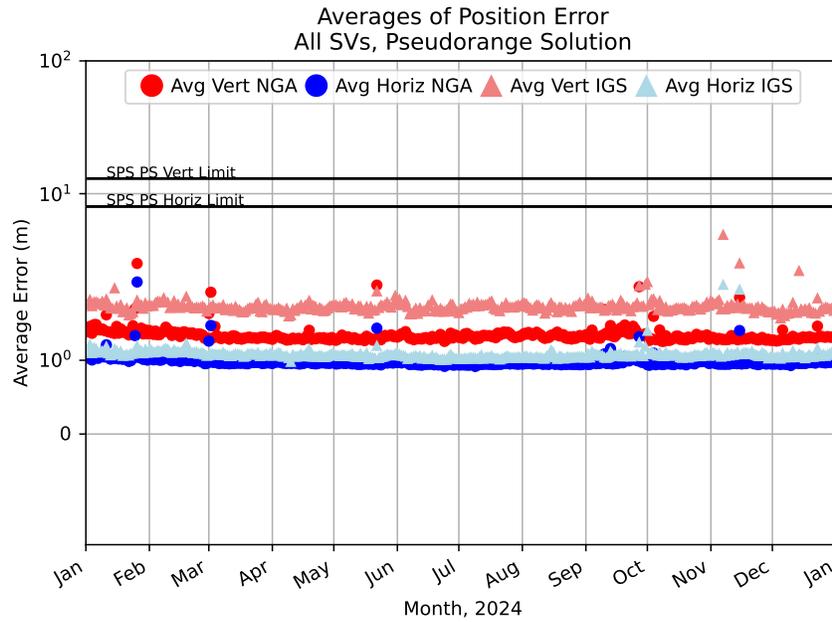


Figure 3.20: Daily Averaged Position Residuals Computed Using No Data Editing

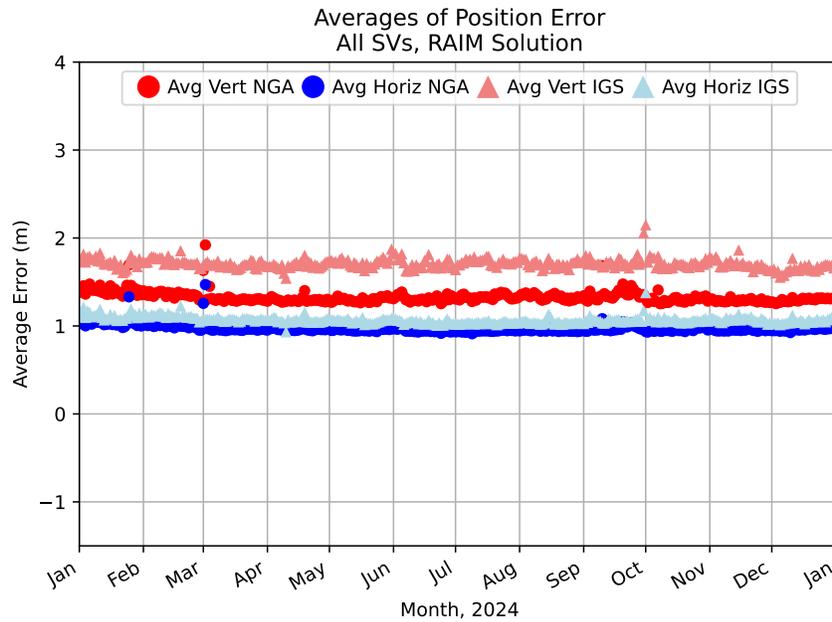


Figure 3.21: Daily Averaged Position Residuals Computed Using a RAIM Solution (enlarged)

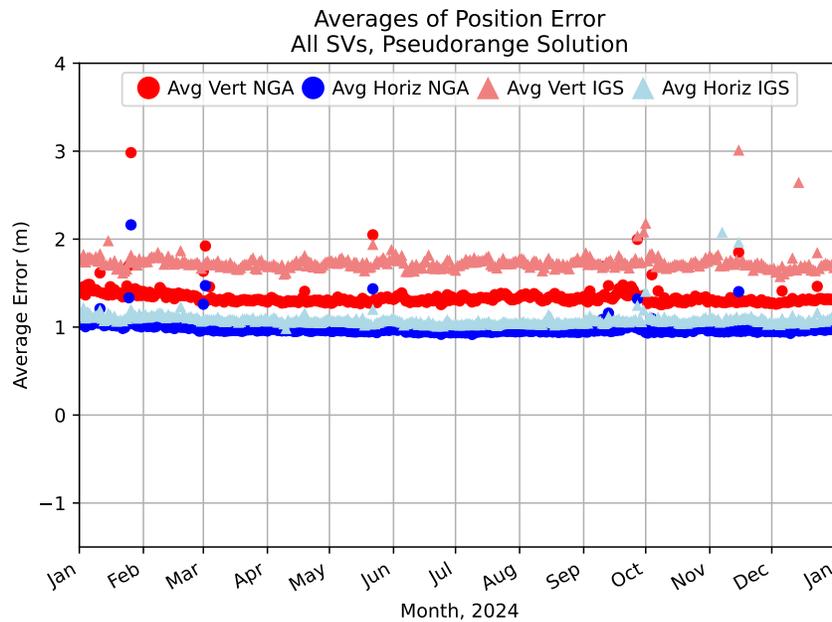


Figure 3.22: Daily Averaged Position Residuals Computed Using No Data Editing (enlarged)

3.6.3.2 Results for Worst Site 95th Percentile

The edited and non-edited 30 s position residuals were then independently processed to determine the worst site 95th percentile values. In this case, the 95th percentile was determined for each station in a given set, and the worst of these was used as the final 95th percentile value for that day. Figures 3.23-3.26 show these values for the various processing options described in the previous section. The plots are preceded by a table of the statistics for the mean, median, maximum, and standard deviation of the daily worst site 95th percentile values.

The statistics associated with the worst site 95th percentile values are provided in Table 3.18. As before, the results are organized in this fashion to facilitate comparison of the same quantity across the various processing options. Values are reported with a precision of one centimeter due to (a) the magnitude of the standard deviation and (b) the fact that the station positions are known only at the few-centimeter level.

Most of the observations from the daily averaged position residuals hold true in the case of the result from the worst site 95th percentile case. However, there are a few additional observations that can be drawn from Figures 3.23-3.26 and Table 3.18 regarding the worst site 95th percentile position solutions:

- The values for both mean and median of the worst 95th percentile for both horizontal and vertical errors are well within the standard for both solutions. Compared to the thresholds of 15 m 95th percentile horizontal and 33 m 95th percentile vertical, these results are outstanding.
- For both data sets, the statistics between the RAIM and pseudorange solutions are similar. However, the maximum value is lower for RAIM solutions. This indicates the importance of data editing in position processing.

Table 3.18: Daily Worst Site 95th Percentile Position Errors for 2024

Statistic	Data Editing	Horizontal		Vertical	
		IGS	NGA	IGS	NGA
Mean (m)	RAIM	4.95	2.72	8.77	4.01
	None	5.06	2.75	8.92	4.02
Median (m)	RAIM	4.99	2.69	8.93	3.93
	None	5.09	2.70	9.06	3.93
Maximum (m)	RAIM	6.19	5.33	10.32	5.67
	None	8.23	5.33	11.79	5.71
Std. Dev. (m)	RAIM	0.34	0.18	0.76	0.40
	None	0.40	0.23	0.78	0.40

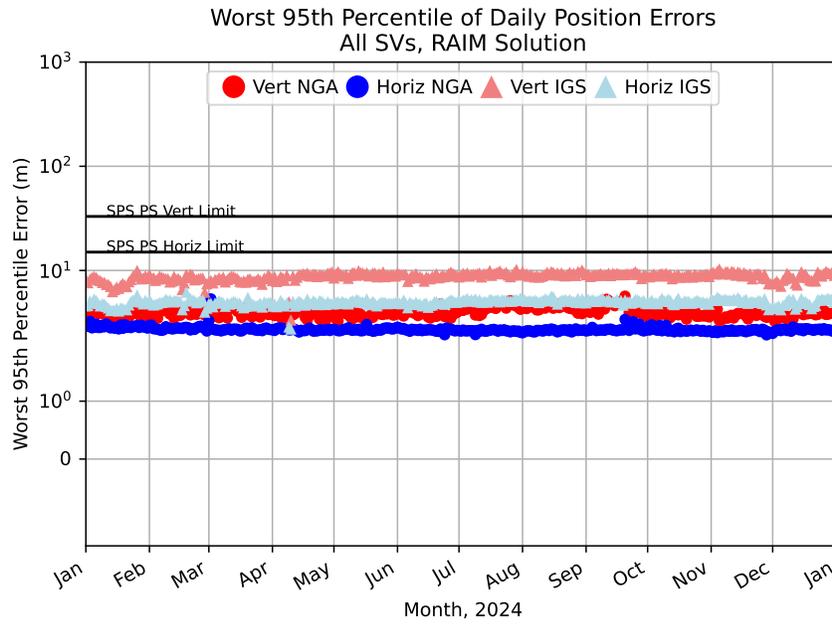


Figure 3.23: Worst Site 95th Daily Averaged Position Residuals Computed Using a RAIM Solution

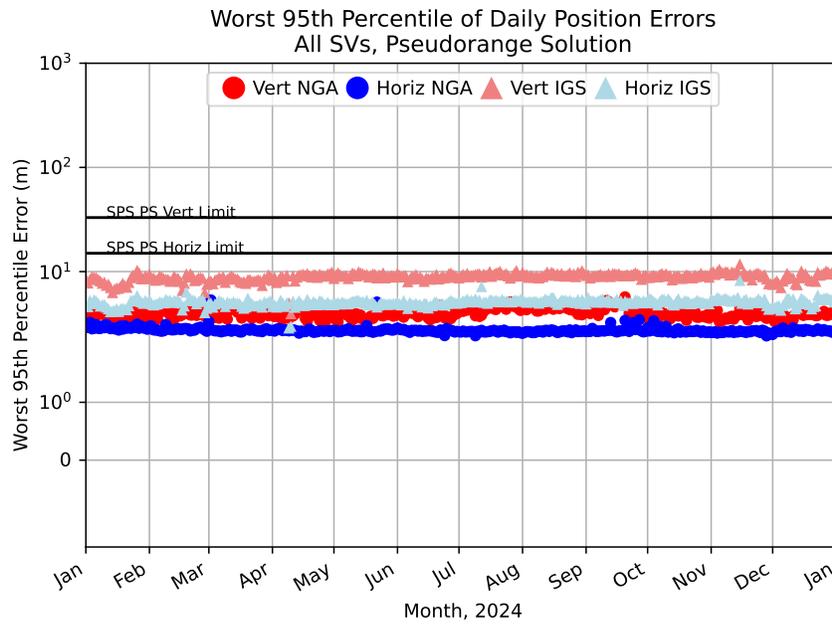


Figure 3.24: Worst Site 95th Daily Averaged Position Residuals Computed Using No Data Editing

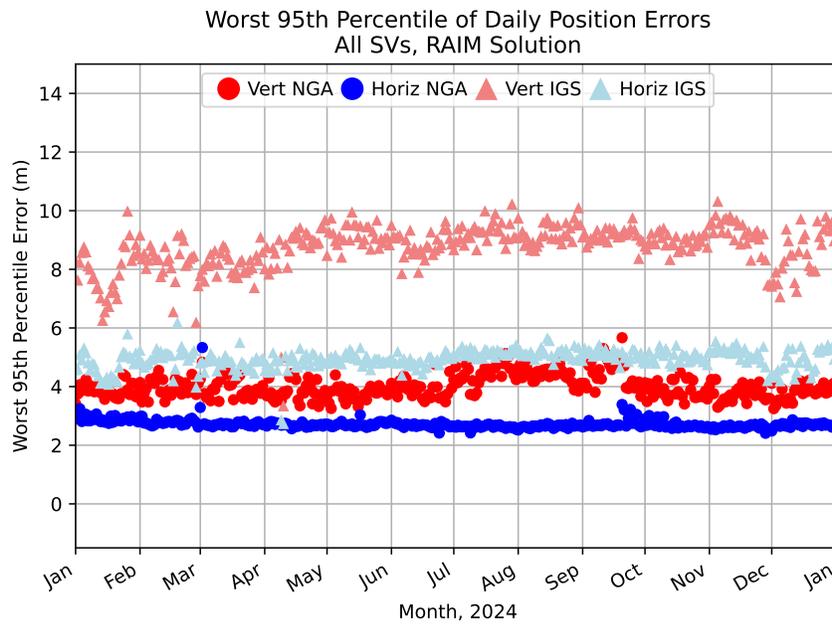


Figure 3.25: Worst Site 95th Daily Averaged Position Residuals Computed Using a RAIM Solution (enlarged)

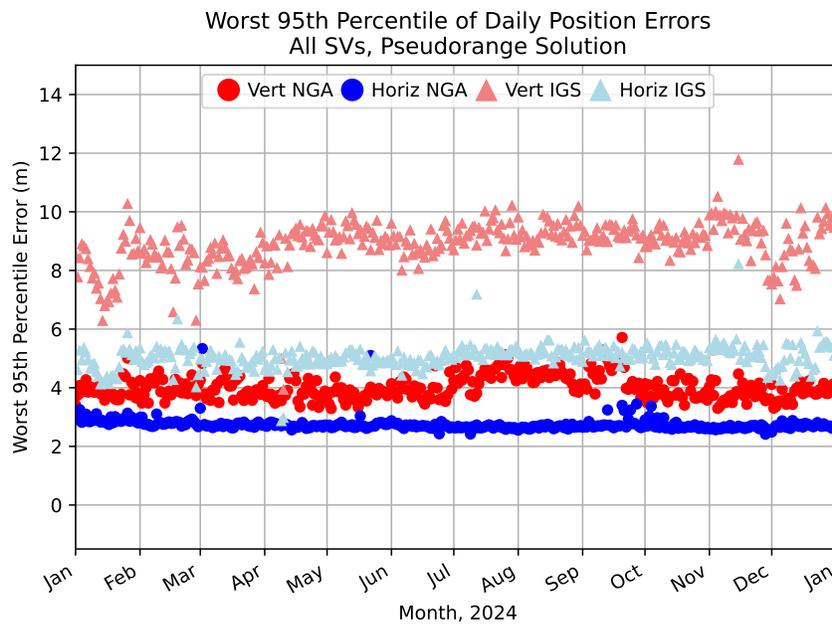


Figure 3.26: Worst Site 95th Daily Averaged Position Residuals Computed Using No Data Editing (enlarged)

3.6.4 Time Transfer Accuracy

The time transfer accuracy standard is stated in Table 3.8-3 of SPS PS 2020 as follows:

- “ ≤ 30 nsec 95% Time Transfer error 95% of the time (SIS only)”

The constraints define this standard as applicable to a time transfer solution “meeting the representative user conditions.”

The equation for time transfer accuracy relative to UTC(USNO), referred to as user UTC(USNO) error (UUTCE), in GPS is found in the SPS PS 2020, Appendix B.2.2.

$$\text{UUTCE} = \sqrt{(\text{UERE} * \text{TTDOP}/c)^2 + (\text{UTC OE})^2}$$

User-equivalent range errors (UERE) can be approximated with URE values. Time transfer dilution of precision (TTDOP) is $1/\sqrt{N}$, where N is the number of satellites visible to the user.¹ The UUTCE calculation was performed for each day of the year.

This computation was done only for satellites that meet the following criteria: trackable, operational, healthy, and having no NANU at each given time. To meet the requirement of an average over all points in the service volume, a worldwide grid with 425 points was created (see Figure 3.27). Because time transfer accuracy can be dependent on which SVs are in view of a given location, the grid was selected to provide a representative sampling of possible user locations around the world with a variety of possible SV combinations. The grid has 10° separation in latitude and longitude at the equator. This yields a spacing of roughly 1,100 km.

Statistics were performed for each day over the grid of 425 points and time step of 15 minutes, resulting in 40,800 points per day to determine the 95th percentile UUTCE value.

The computation steps are:

1. Compute satellite positions for each time point in the day using the broadcast ephemeris,
2. For each time and grid point,
 - (a) find visible satellites (above 5° elevation) that meet the above criteria,
 - (b) determine the appropriate UTCO data set (UTC O_i). The appropriate data set is the valid data set that has the latest reference time (t_{ot}) of all valid data sets received at that location at that time. Calculate $\text{UTC OE}_i = \text{UTC O}_i - \text{USNO}$, where USNO is the daily published value,
 - (c) get the instantaneous SIS URE for each visible satellite, then take the mean of all values (UERE_i) and assign as the value for that time and grid point,
3. Calculate all 40,800 UUTCE values for the day, find 95% containment of all values.

¹as per conversation with Mr. Karl Kovach, author of the SPS PS, 31 August 2017

The daily UUTCE results over all grid points and times per day are shown in Figure 3.28. All of these results are well below 30 nsec. Therefore, this assertion is met.

Lat/Lon Grid with 10 degree spacing (425 points)

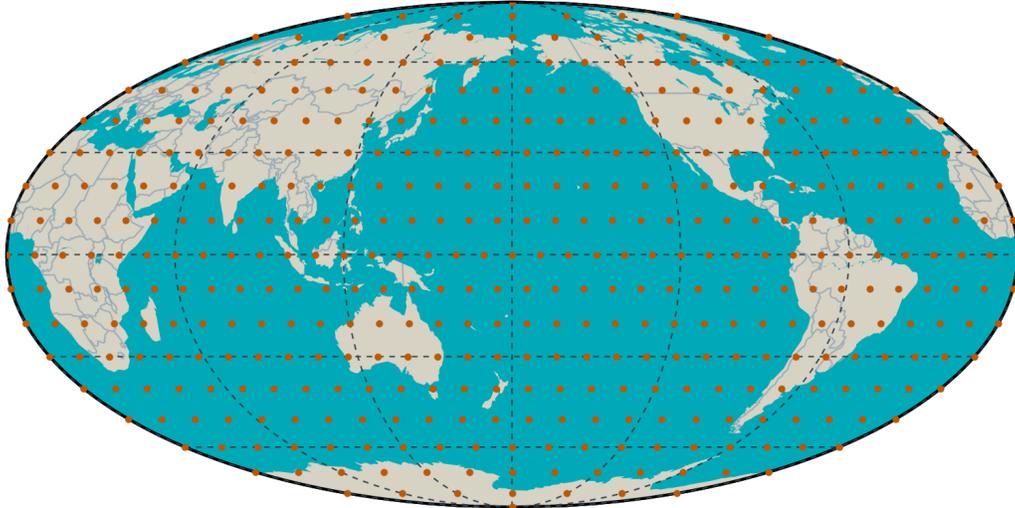


Figure 3.27: 10° Grid for UUTCE Calculation

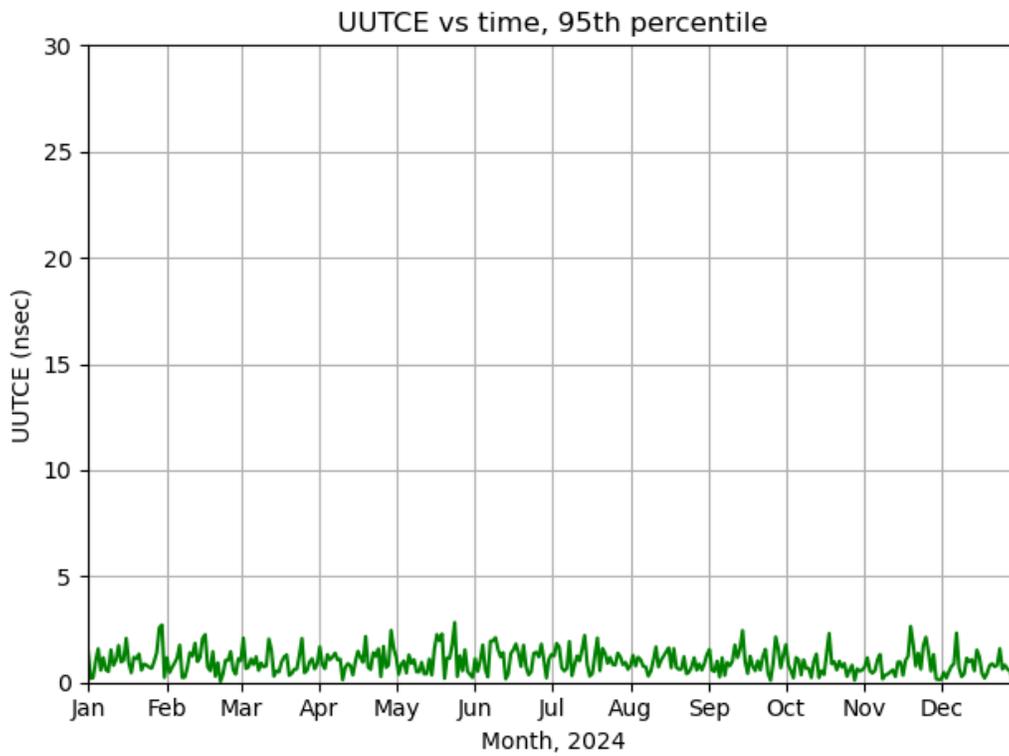


Figure 3.28: UUTCE 95th Percentile Values

Appendix A

Additional Results of Interest

This chapter provides additional results of interest. These results support the conclusions drawn earlier in the report while providing additional insight into satellite health values, age of data, user range accuracy values, extended mode operations, URE as a function of AOD, descriptions of notable events, and additional DOP analysis.

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A.1 Health Values

Several of the assertions require examination of the health information transmitted by each SV. We have found it useful to examine the rate of occurrence for all possible combinations of the six health bits transmitted in subframe 1. We examined all unique navigation messages received in 2024. There are typically 13 unique messages per day for each SV. This leads to approximately 4,750 unique messages for each year for an SV.

Table A.1 presents a summary of health bit usage in the ephemerides broadcast during 2024. Each row in the table presents a summary for a specific SV. The summary across all SVs is shown at the bottom. The table contains the number of times each unique health code was seen, the raw count of unique subframe 1 messages collected during the year, and the percentage of subframe 1 messages that contained specific health codes. Three unique health settings were observed throughout 2024: binary 111111_2 (0x3F), binary 111100_2 (0x3C), and binary 000000_2 (0x00).

Table A.1: Distribution of SV Health Values

SVN	PRN	Count by Health Code			Total # Subframe 1 Collected	% of Time by Health Code			Operational Days for 2024	Average # Subframe 1 per Operational Day
		0x3F	0x3C	0x00		0x3F	0x3C	0x00		
43	13	4	0	4924	4928	0.1	0.0	99.9	366	13.5
44	22	0	0	4598	4598	0.0	0.0	100.0	351	13.1
45	21	32	0	5011	5043	0.6	0.0	99.4	366	13.8
48	07	141	0	4832	4973	2.8	0.0	97.2	366	13.6
50	05	3	0	4835	4838	0.1	0.0	99.9	366	13.2
51	20	4	0	4844	4848	0.1	0.0	99.9	366	13.2
52	31	4	0	4858	4862	0.1	0.0	99.9	366	13.3
53	17	43	0	4918	4961	0.9	0.0	99.1	366	13.6
55	15	0	0	4792	4792	0.0	0.0	100.0	366	13.1
56	16	4	0	4797	4801	0.1	0.0	99.9	366	13.1
57	29	6	0	4921	4927	0.1	0.0	99.9	366	13.5
58	12	0	4	4799	4803	0.0	0.1	99.9	366	13.1
59	19	4	0	4812	4816	0.1	0.0	99.9	366	13.2
61	02	4	0	4865	4869	0.1	0.0	99.9	366	13.3
62	25	4	0	4808	4812	0.1	0.0	99.9	366	13.1
64	30	0	4	4808	4812	0.0	0.1	99.9	366	13.1
65	24	4	0	4790	4794	0.1	0.0	99.9	366	13.1
66	27	102	0	4412	4514	2.3	0.0	97.7	342	13.2
67	06	15	0	4810	4825	0.3	0.0	99.7	366	13.2
68	09	4	0	4796	4800	0.1	0.0	99.9	366	13.1
69	03	4	0	5159	5163	0.1	0.0	99.9	366	14.1
70	32	0	0	4779	4779	0.0	0.0	100.0	366	13.1
71	26	0	0	4877	4877	0.0	0.0	100.0	366	13.3
72	08	79	0	4808	4887	1.6	0.0	98.4	366	13.4
73	10	87	0	4801	4888	1.8	0.0	98.2	366	13.4
74	04	4	0	4747	4751	0.1	0.0	99.9	366	13.0
75	18	6	0	4744	4750	0.1	0.0	99.9	366	13.0
76	23	4	0	4704	4708	0.1	0.0	99.9	366	12.9
77	14	0	0	4740	4740	0.0	0.0	100.0	366	13.0
78	11	5	0	4744	4749	0.1	0.0	99.9	366	13.0
79	28	0	0	4730	4730	0.0	0.0	100.0	366	12.9
All SVs		567	8	149063	149638	0.4	0.0	99.6	366	408.8

A.2 Age of Data

The Age of Data (AOD) represents the elapsed time between the observations that were used to create the broadcast navigation message and the time when the contents of subframes 1, 2, and 3 became available to the user to estimate the position of an SV. The accuracy of GPS (for users that depend on the broadcast ephemeris) is indirectly tied to the AOD because the prediction accuracy degrades over time (see Section 3.2.2). This is especially true for the clock prediction.

It has been recognized that reducing the AOD improves position, velocity, and time (PVT) solutions for autonomous users; however, there is an impact in terms of increased operations tempo at 2 NWS. Note that there is no need for a GPS receiver to refer to AOD in any PVT computation. The AOD is computed here to validate that the operators at 2 NWS are maintaining the URE accuracy with a normal operational tempo.

The daily average AOD throughout 2024 is shown in Table A.2, along with values for the previous three years. Details on how AOD was computed are provided in Appendix C.4.

Figure A.1 illustrates the daily average AOD for the constellation and the various sub-constellations by SV type. The decrease in average AOD starting in February was due to a change in operations tempo at 2 NWS. The average AOD from March through the end of the year is generally constant, which indicates that variations in the URE results for this period were not due to changes in operations tempo. The brief increases in AOD in April, May, and September were due to some satellites entering short-term extended nav mode.

Table A.2: Age of Data of the Navigation Message by SV Type

	Average Age of Data (hrs)			
	2021	2022	2023	2024
Full Constellation	12.1	12.0	11.9	11.1
Block IIR/IIR-M	12.0	12.0	11.9	10.8
Block IIF	12.0	11.9	11.6	11.0
GPS III	12.3	12.3	12.1	12.1

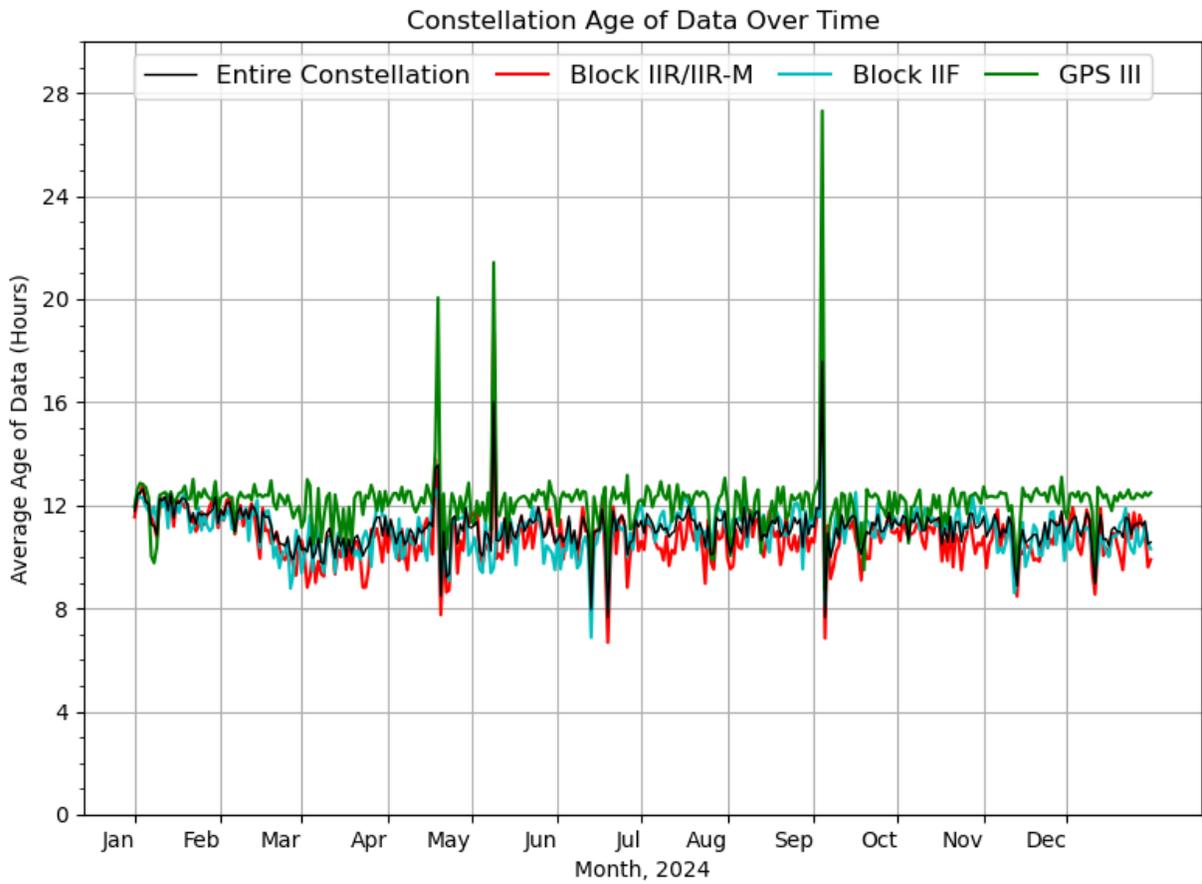


Figure A.1: Constellation Age of Data for 2024

A.3 User Range Accuracy Index Values

Figure A.2 presents the number of 30 s periods in the year in which an SV transmitted a given LNAV URA index. Only periods in which the SV was transmitting a healthy indication are included. SVs that were operational only part of the year have lower total counts.

The vast majority of the broadcast LNAV URA indices are 0, 1, or 2 (over 99.9%). Index values of 3, 4 and 5 were very rare. No index values over 5 were observed.

Analysis of the URA values derived from the CNAV data requires a slightly different approach. Because the CNAV URA is a continuous function, we computed the CNAV URA value at each 30 s epoch, then binned those values corresponding to the range of LNAV URA values in IS-GPS-200 Section 20.3.3.3.1.3. That is to say, LNAV URA Index 1 has a range of 2.40 to 3.40 m; therefore, the CNAV URA values that fall into that range are assigned to Bin 1. CNAV URA values with values of 0.00 to 2.40 m are assigned to Bin 0.

Figure A.3 presents the number of 30 s periods in the year in which an SV transmitted a CNAV URA value that falls into the specified bins. There are a smaller number of SVs due to the fact the Block IIR SVs do not transmit a CNAV message.

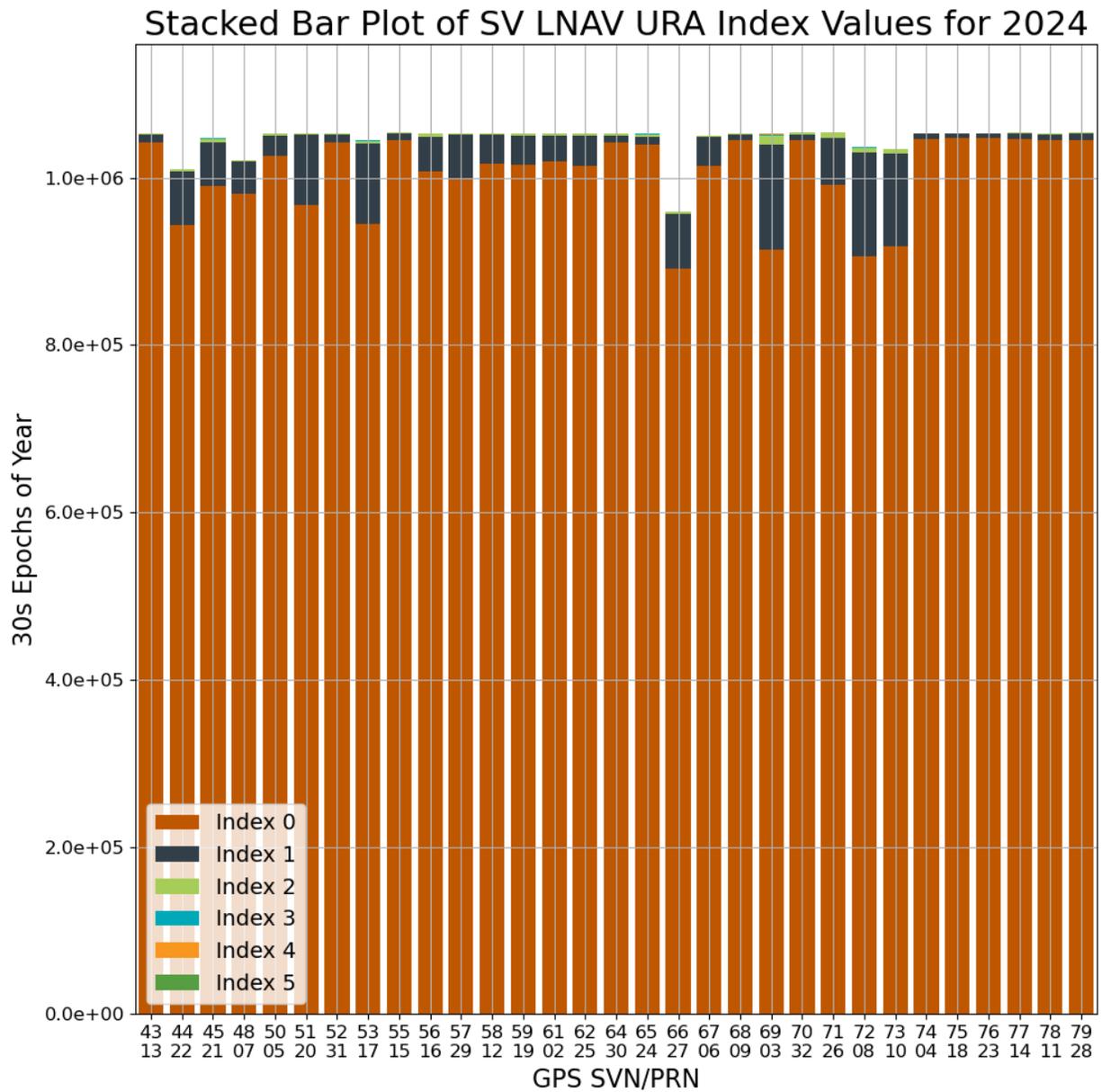


Figure A.2: Stacked Bar Plot of SV LNAV URA Index Values for 2024

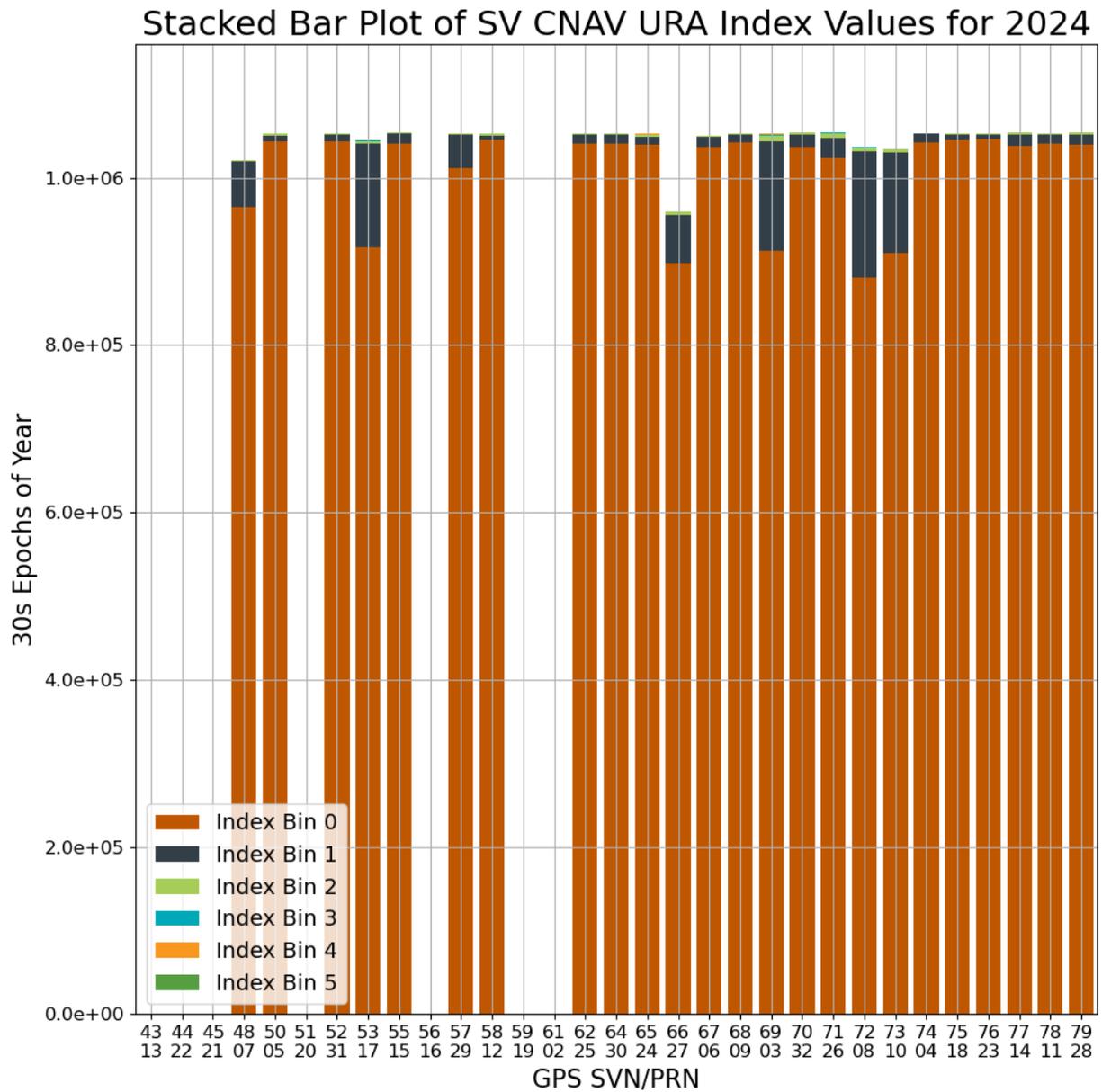


Figure A.3: Stacked Bar Plot of Binned SV CNAV URA Index Values for 2024

A.4 Extended Mode Operations

IS-GPS-200 defines Normal Operations as the period of time when subframe 1, 2, and 3 data sets are transmitted by the SV for periods of two hours with a curve fit interval of four hours (IS-GPS-200 Section 20.3.4.4). This definition is taken to be the same as the definition of Normal Operations in SPS PS 2020 for the URE metrics. To determine if any SV operated outside of Normal Operations at any time in 2024, the broadcast ephemerides were examined to determine if any contained fit interval flags that were set to 1. (See IS-GPS-200 20.3.3.4.3.1 for definition of the fit interval flag).

The analysis found a total of 66 examples of extended operations for satellites set healthy. The examples were distributed across 16 days. The average time of an occurrence was 4 hours 24 minutes. The minimum duration was 8 minutes and the maximum duration was 20 hours 24.5 minutes. These results are summarized in Table A.3.

Given the relative rarity of occurrence, the URE values for the periods summarized in Table A.3 are included in the statistics presented in Section 3.2.1, even though a strict interpretation of the SPS PS 2020 would suggest that they be removed. However, the SVs involved were still set healthy and (presumably) being used by user equipment, so it is appropriate to include these results to reflect performance seen by the users.

Examination of the ephemerides from past years reveals that 2024 is not an anomaly. Such periods have been found in all years checked, dating back to 2005.

Past discussions with the operators have revealed several reasons for these occurrences. Some are associated with Alternate MCS (AMCS) testing. When operations are transitioned from the MCS to the AMCS (and reverse), it is possible that SVs nearing the end of their daily cycle may experience a longer-than-normal upload cycle. Other occurrences may be caused by delays due to ground antenna maintenance or due to operator concentration on higher-priority issues with the constellation at the time.

Table A.3: Summary of Occurrences of Extended Mode Operations

SVN	PRN	# of Occurrences		Duration (minutes)	
		Healthy	Unhealthy	Healthy	Unhealthy
43	13	2	0	654	0
44	22	3	0	1315	0
45	21	3	0	962	0
48	07	2	0	1008	0
50	05	4	0	1725	0
51	20	2	0	739	0
52	31	2	0	1556	0
53	17	4	0	1727	0
55	15	2	0	1068	0
56	16	2	0	1445	0
57	29	2	0	1219	0
58	12	3	0	838	0
59	19	4	0	1574	0
61	02	3	0	1230	0
62	25	2	0	1484	0
64	30	3	0	1380	0
65	24	4	0	2009	0
66	27	0	1	0	1011
67	06	4	0	1470	0
68	09	4	0	1536	0
69	03	3	0	1246	0
70	32	3	0	2304	0
71	26	1	0	719	0
72	08	2	0	1370	0
73	10	2	0	1707	0
Totals		66	1	32285	1011

A.5 URE as a Function of AOD

This appendix contains supporting information for the results presented in Section 3.2.2. Charts of SIS RMS URE vs. AOD similar to Figures 3.5 - 3.12 are presented for each GPS SV. The charts are organized by SV block and by ascending SVN within each block. These charts are based on the set of 30 s instantaneous SIS RMS URE values computed as described in Appendix C.2.4. AOD values were computed as described in Appendix C.4. For each SV, the entire year of 30 s URE values was grouped by AOD in bins of 15 minutes each. The URE values in each bin were sorted and the 95th percentile was determined.

For satellites averaging one upload per day, the count of points in each bin is roughly constant from the time the upload becomes available until about 24 hours AOD. The nominal number of points can be calculated by multiplying the number of expected 30 s estimates in a 15 minute bin (30 estimates per bin) by the number of days in the year. There are just under 11,000 points in each such bin.

Since GPS SVs are typically uploaded at least once per day, bins beyond 24 hours AOD are sparsely populated. Bins with few points tend to be dominated by occasional high-value outliers that can lead to erroneous conclusions about behavior. Therefore, bins containing fewer than 10% of points relative to the maximum populated bin were dropped before plotting.

The count of points in each bin as a function of AOD for L1 C/A are plotted. This is representative of the curves for other signal combinations for a given SV as the unhealthy periods for all signals for a given SV are very nearly coordinated.

Note that for most SVs, the green counts curve has a well-defined slope that begins near zero AOD, continues for roughly 24 hours, and then drops quickly toward zero. For satellites with an average of one upload per day, the count of points in each bin is roughly constant from the time the upload becomes available until about 24 hours AOD. This corresponds to a plateau of the green curve. For satellites averaging more than one upload per day, the green curve will show a left-hand peak decreasing to the right. This is a result of there being fewer points at higher AOD due to the more frequent uploads.

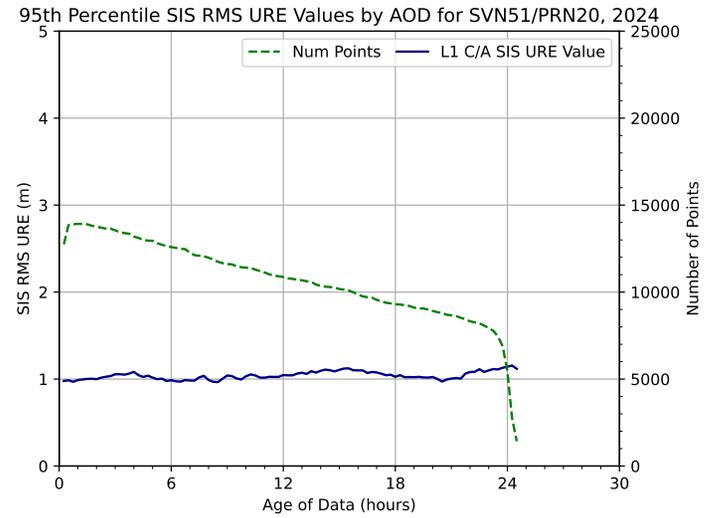
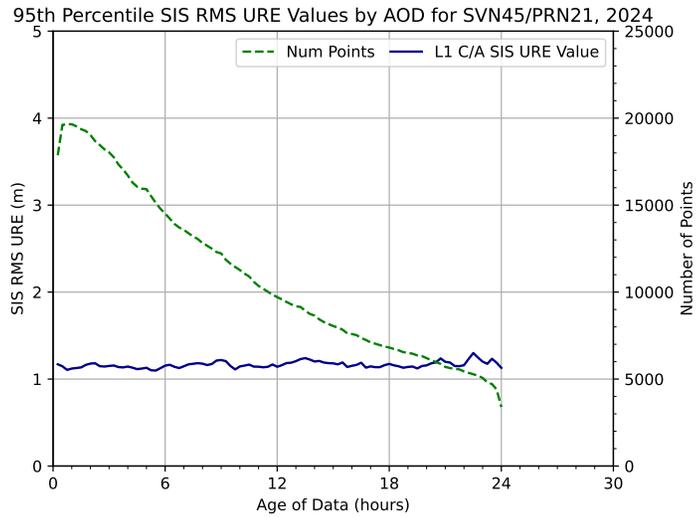
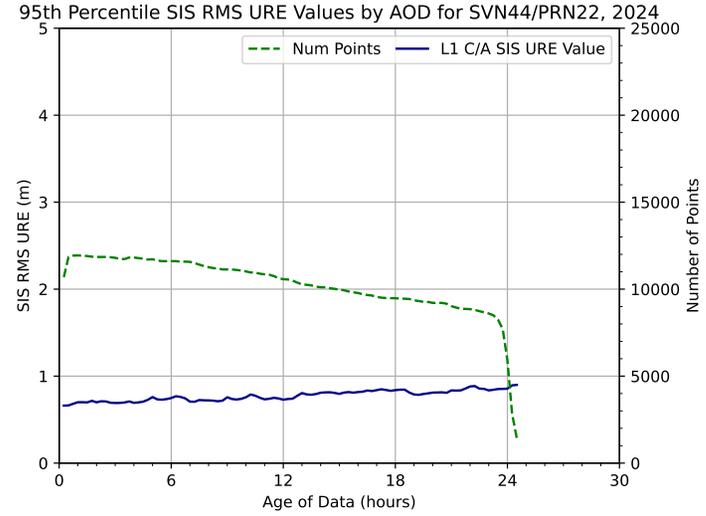
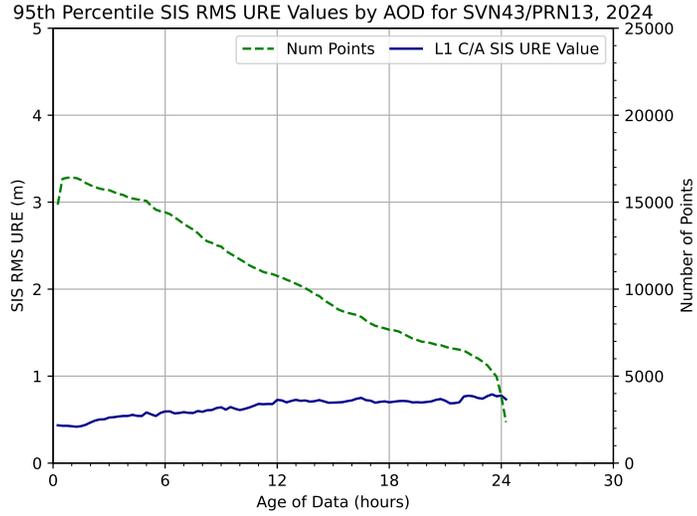
Where multiple curves are present, the biases between the curves are a result of the influence of the ISC and DCB values on the URE calculation process. See Appendix C.2.2, Appendix C.2.5, and Appendix C.2.6 for details.

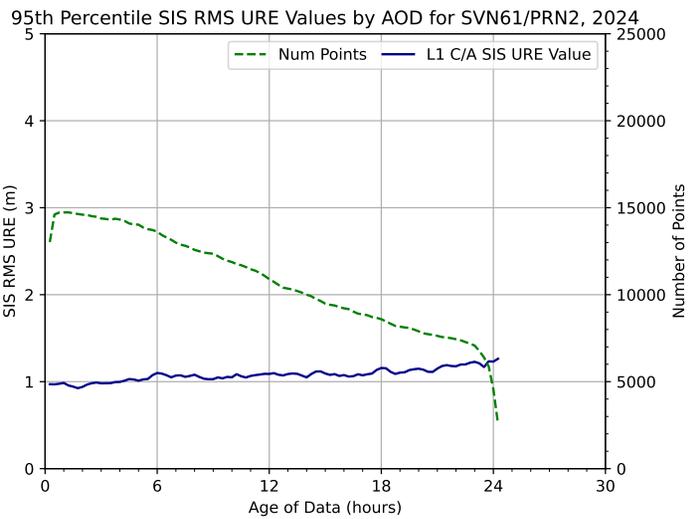
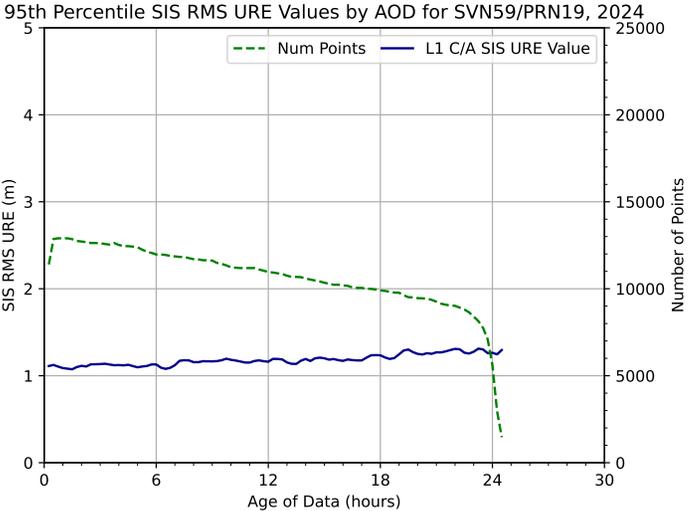
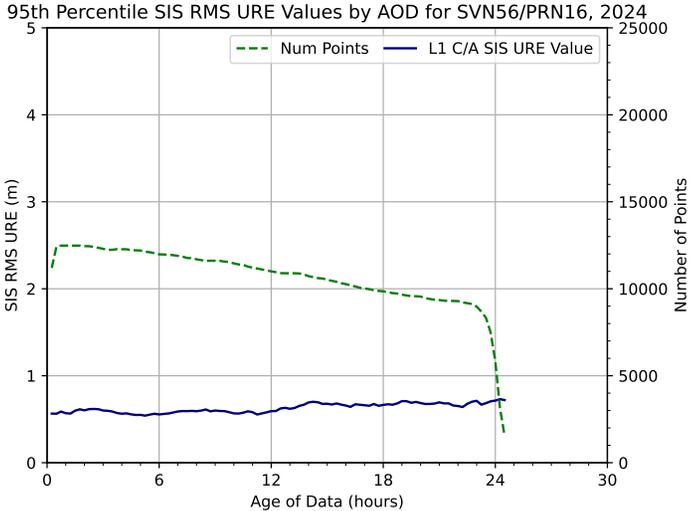
A.5.1 SPS Results

The figures on the following pages each show up to four curves:

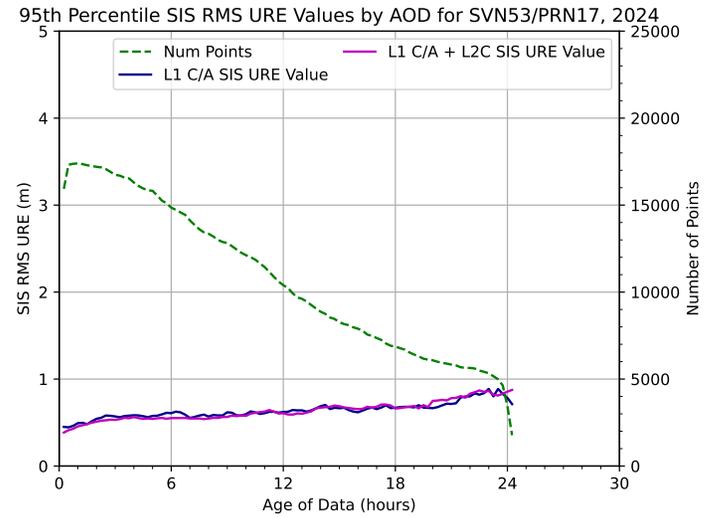
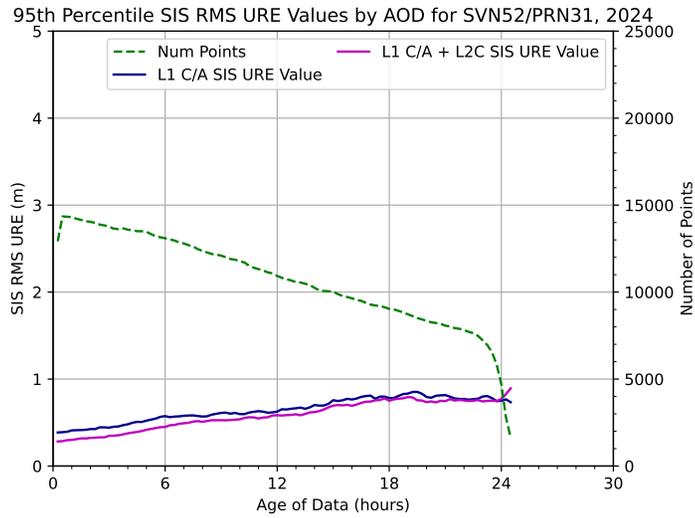
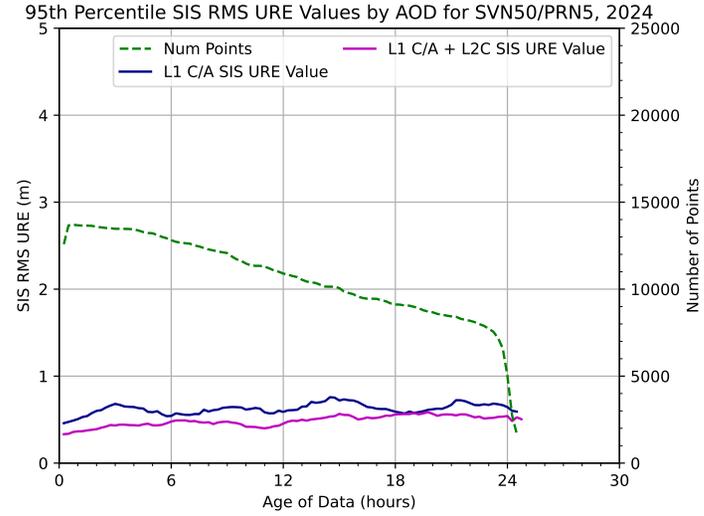
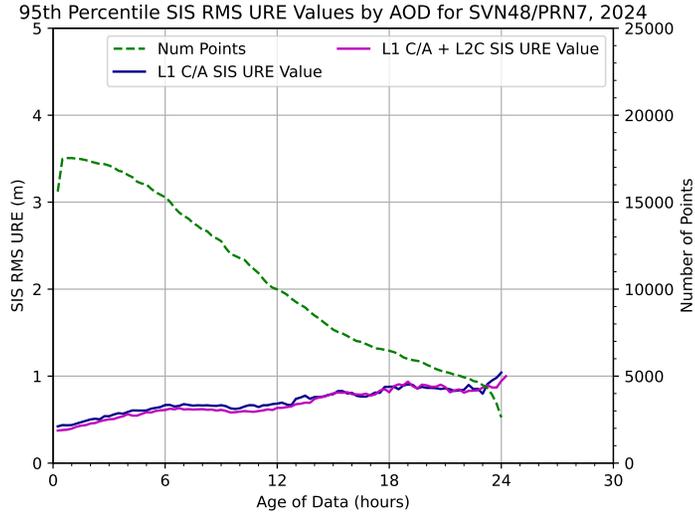
- 95th percentile URE vs. AOD for:
 - **Blue**: L1 C/A
 - **Magenta**: L1 C/A + L2C
 - **Cyan**: L1 C/A + L5Q
- **Green**: count of points in each bin vs. AOD for L1 C/A

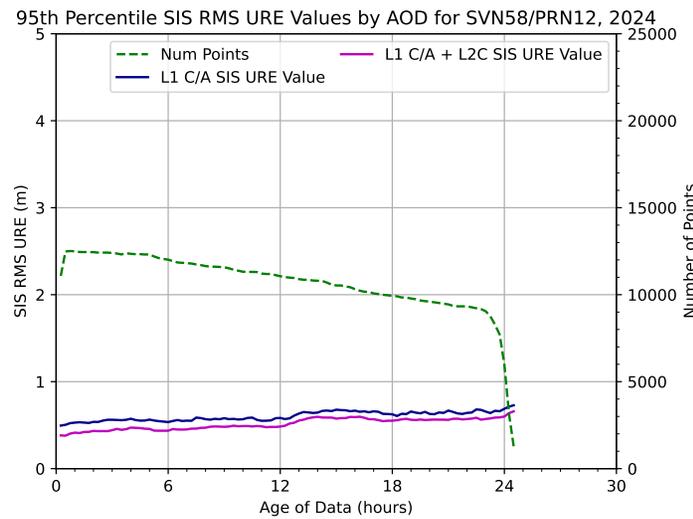
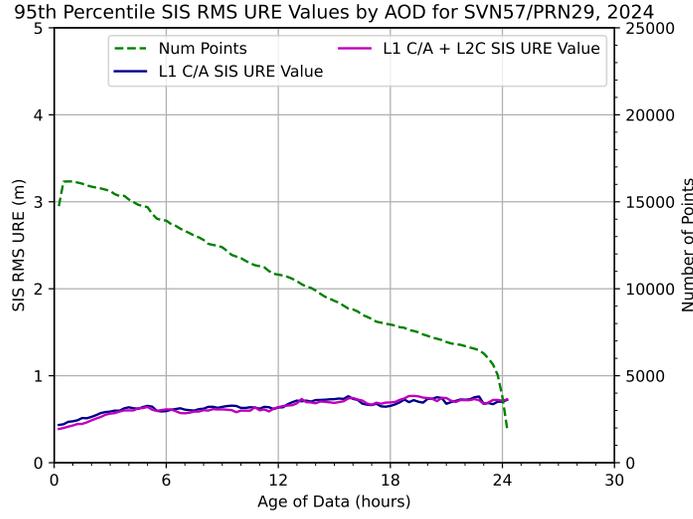
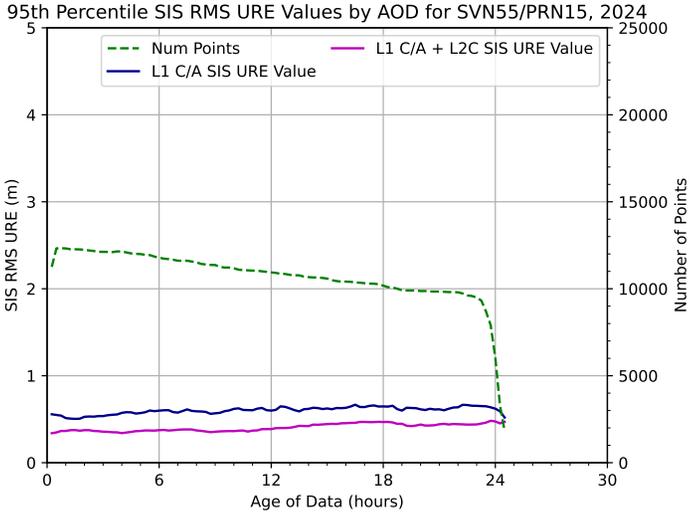
A.5.1.1 Block IIR SVs



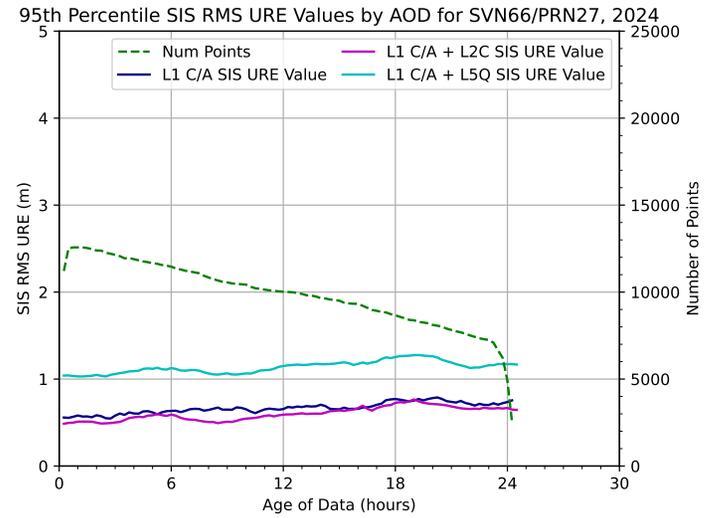
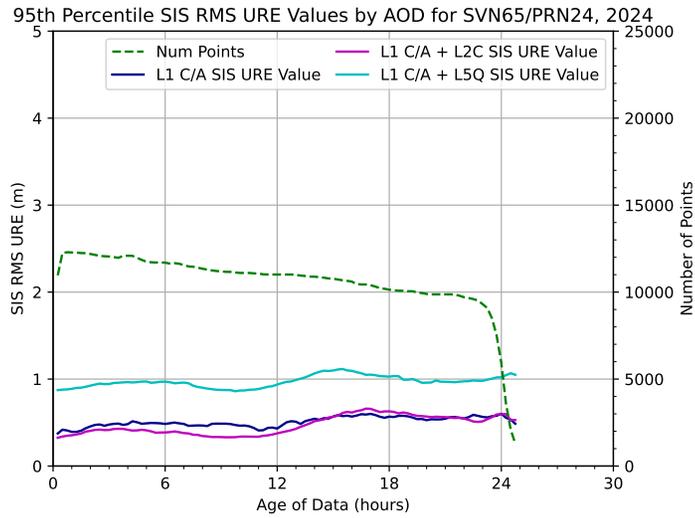
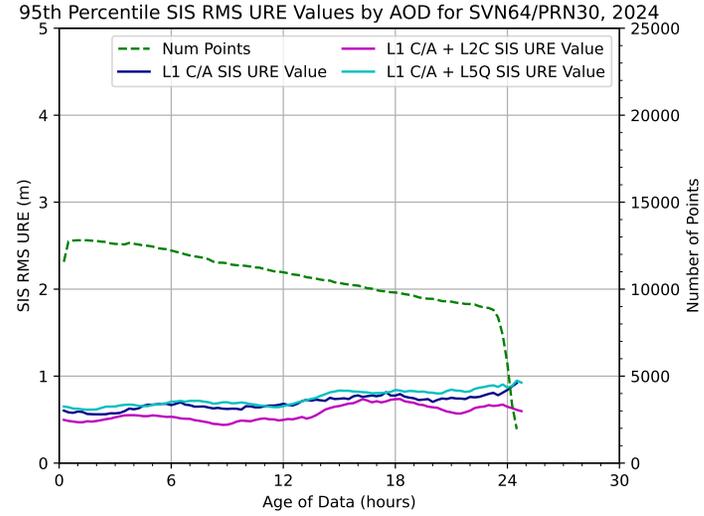
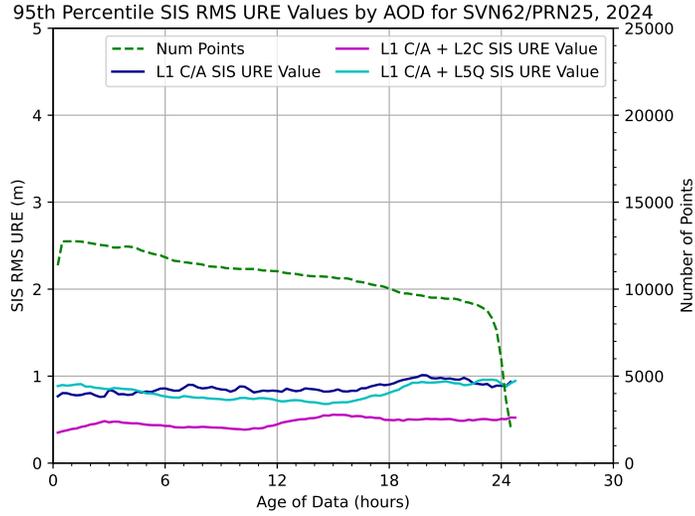


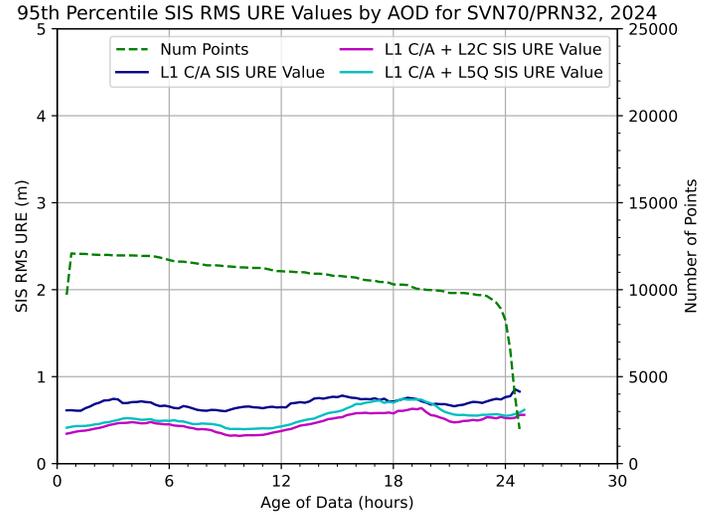
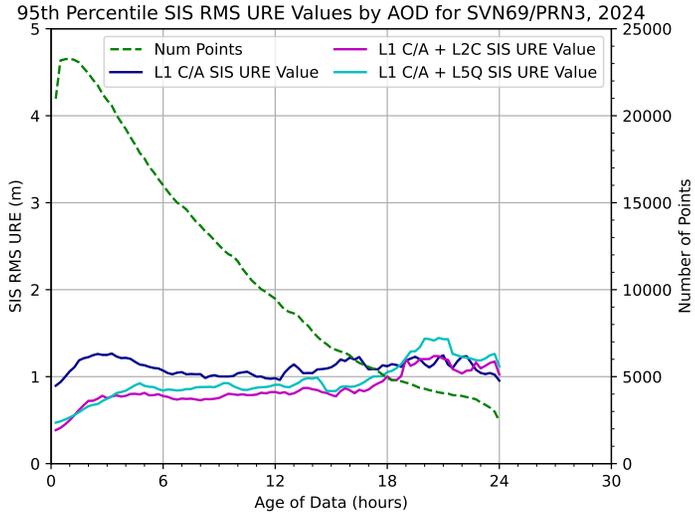
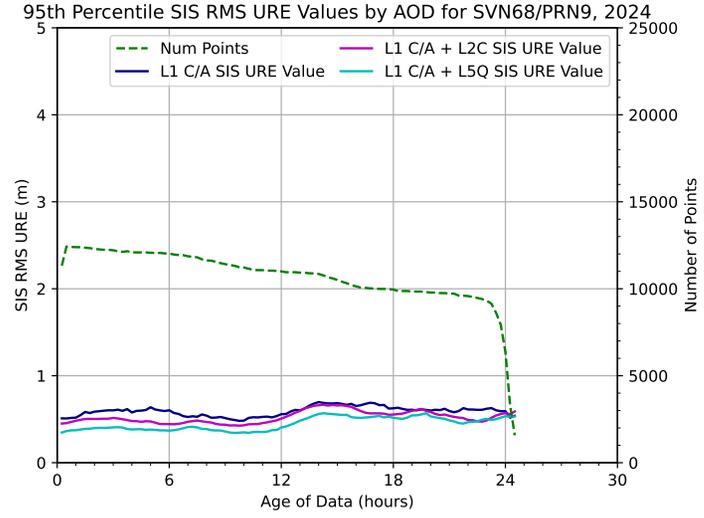
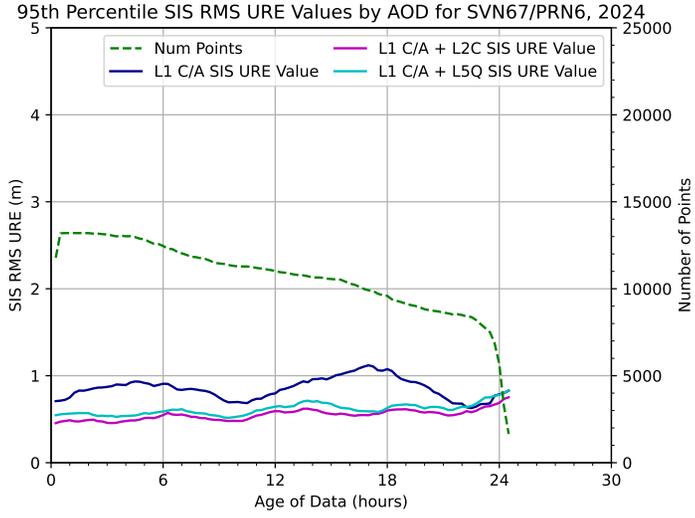
A.5.1.2 Block IIR-M SVs

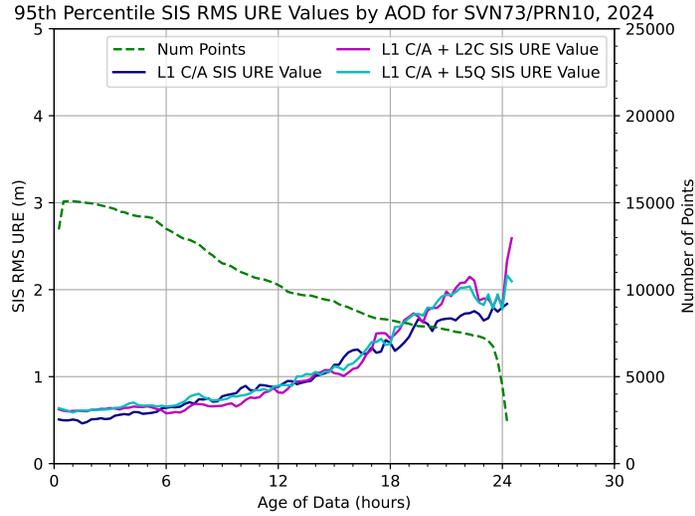
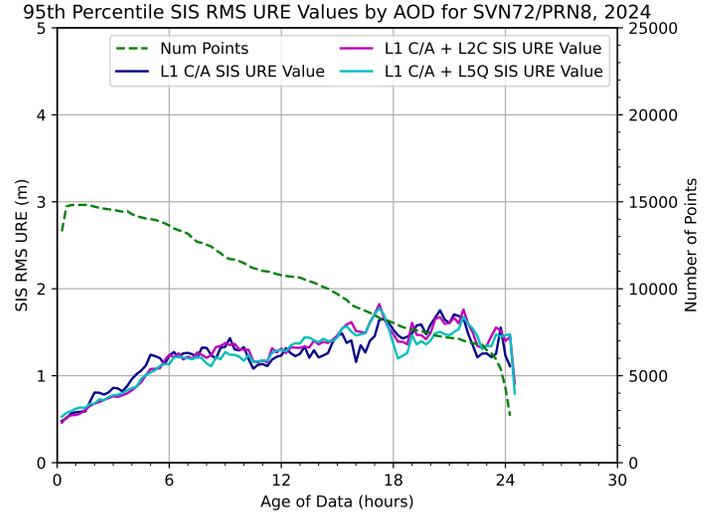
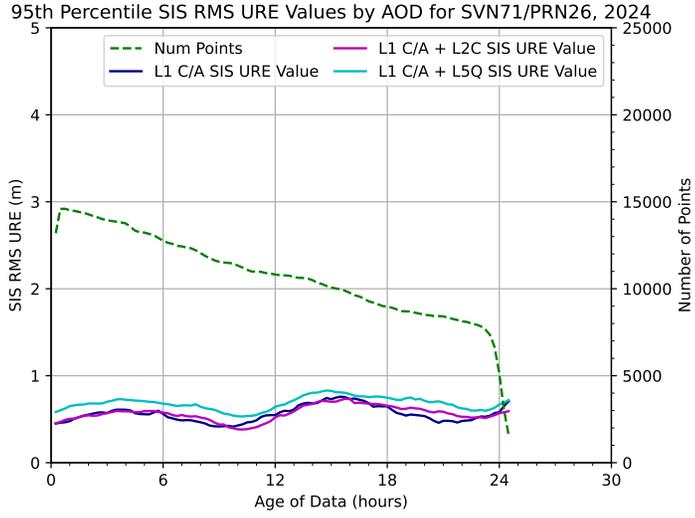




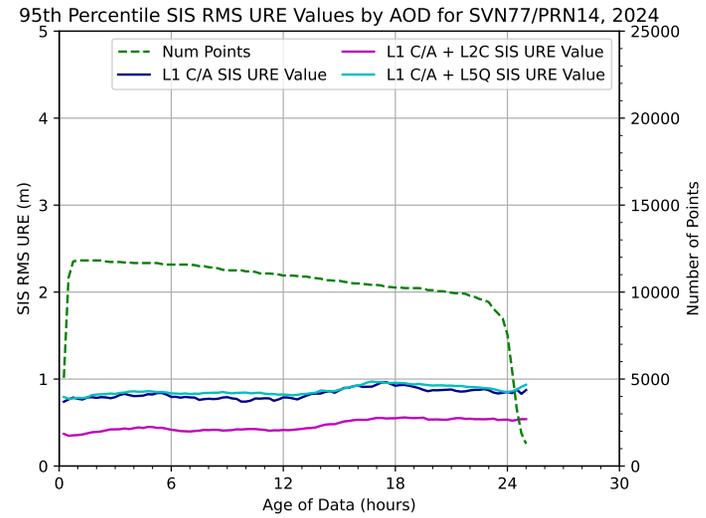
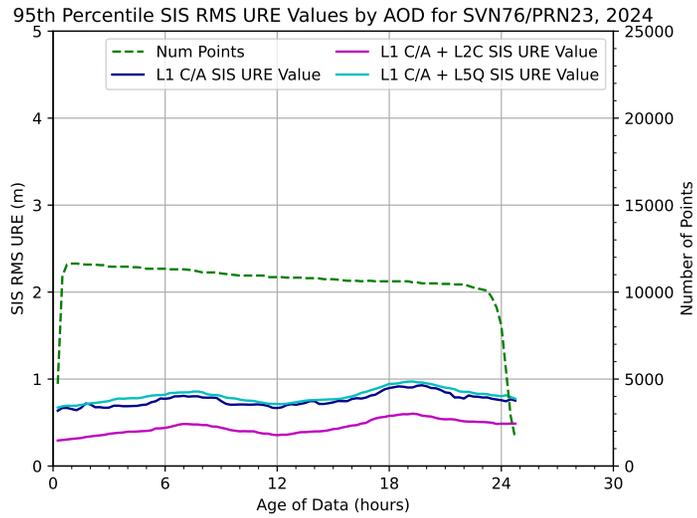
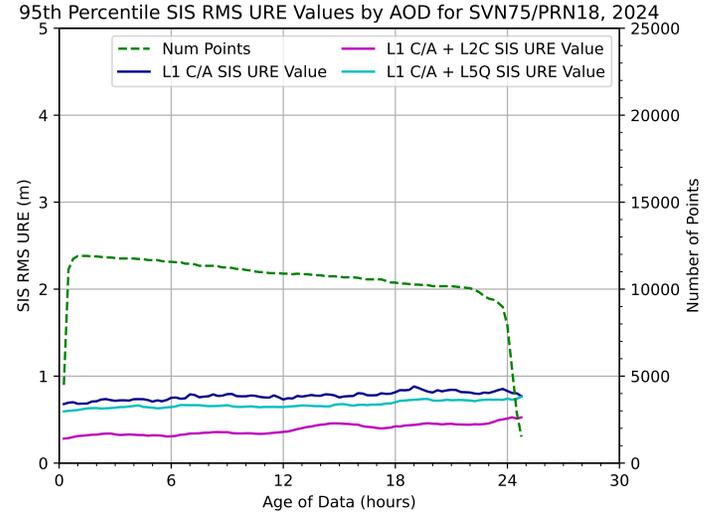
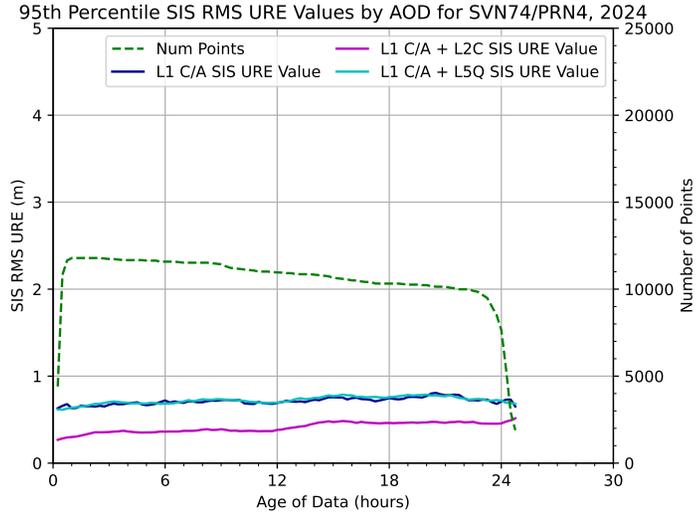
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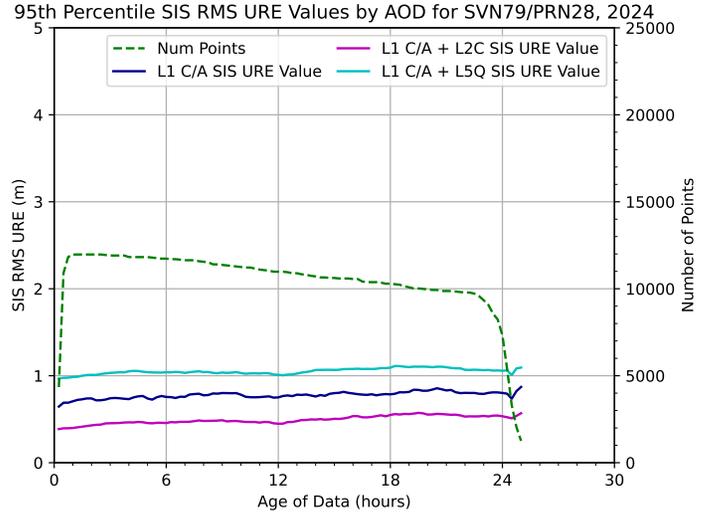
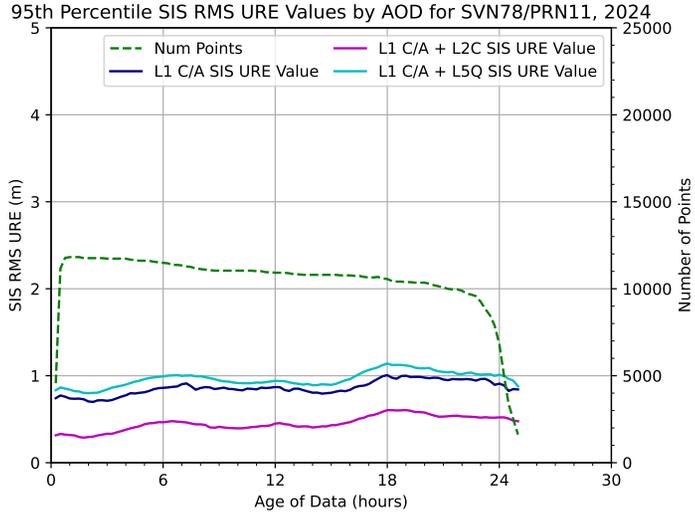






A.5.1.4 GPS III SVs





A.6 Integrity Fault Events

During 2024, there were four periods in which a satellite had an integrity fault event on at least one signal. As discussed in Section 3.3.1 and Section 3.3.3, an integrity fault event is defined to occur when the SIS instantaneous URE on a healthy satellite exceeds the NTE tolerance. The NTE tolerance is defined as ± 4.42 times the upper bound on the user range accuracy (URA) currently broadcast by the satellite.

Table A.4 lists the integrity fault events for each signal during 2024. Table A.5 summarizes the integrity fault events for each signal.

L5 is currently set unhealthy and is pre-operational; results are included for reference. Note that start and end times for integrity fault events may vary between signals due to different URA thresholds and signal health status changes.

Table A.4: Integrity Fault Events for 2024

Signal	SVN	PRN	Start Time	End Time	Duration (min)	Max. URE (m)
L1 C/A	48	7	25 May 15:47:00	25 May 16:21:30	34.5	40.26
L1 C/A + L2C	53	17	17 May 00:29:30	17 May 01:25:00	55.5	7.07
L1 C/A + L2C	48	7	25 May 15:45:30	25 May 16:29:30	44.0	39.71
L1 C/A + L2C	71	26	01 Nov 19:06:00	01 Nov 19:27:00	21.0	3.80
L1 C/A + L2C	71	26	03 Nov 01:06:30	03 Nov 01:29:00	22.5	3.65
L1 C/A + L5Q	71	26	01 Nov 19:10:00	01 Nov 19:26:30	16.5	3.60
L1 C/A + L5Q	71	26	03 Nov 01:17:00	03 Nov 01:28:30	11.5	3.49

Table A.5: Integrity Fault Events Summary for 2024

Signal	Count	Duration (min)
L1 C/A	1	34.5
L1 C/A + L2C	4	143.0
L1 C/A + L5Q	2	28.0

Appendices A.6.1 through A.6.3 provide a more detailed description of each event and corresponding figures. Each figure shows the SIS RMS URE and the range of SIS instantaneous URE values for the signal of interest, and the NTE tolerance threshold of 4.42 times the broadcast URA for the period of interest. Regions shaded gray indicate periods in which the satellite was not transmitting. Regions shaded red indicate periods in which the satellite was broadcasting with an unhealthy indication. Note that there is a difference in cadence between the SIS RMS (30 s) and instantaneous (5 min) UREs.

A.6.1 17 May SVN 53/PRN 17 Event

On 17 May 2024, SVN 53/PRN 17 exceeded the L2C CNAV NTE URE integrity threshold. Figure A.4 shows the SIS RMS URE and the range of SIS instantaneous URE values for L1 CA + L2C, and 4.42 times the broadcast LNAV and L2C CNAV URA NTE thresholds for the period of interest. The shaded regions reflect L2C signal status.

The fault period lasted for 55.5 minutes between 00:29:30 and 01:25:00, with an L2C NTE threshold ranging from 3.75 m at the start of this period to 4.08 m at the end.

The satellite broadcast L2C from the start of the day until 00:10:51. The satellite began L2C transmission again at 00:29:30. An error in the clock offset term resulted in a maximum SIS instantaneous URE of 7.07 m after transmission resumed, exceeding the L2C NTE threshold. The fault period continued until the satellite again ceased broadcast of the L2C signal at 01:25:00. Transmission began again at 02:07:20 with an unhealthy indication, with an upload at 06:13:36 correcting the clock offset term and lowering the UREs. At 20:22:24 the satellite returned to a healthy signal.

Note that while the L2C CNAV NTE threshold was exceeded during this event, Figure A.4 shows the LNAV NTE threshold during this event was 10.608 m. Additionally, this satellite does not broadcast on L5. As a result, this event occurred only on L1 C/A + L2C.

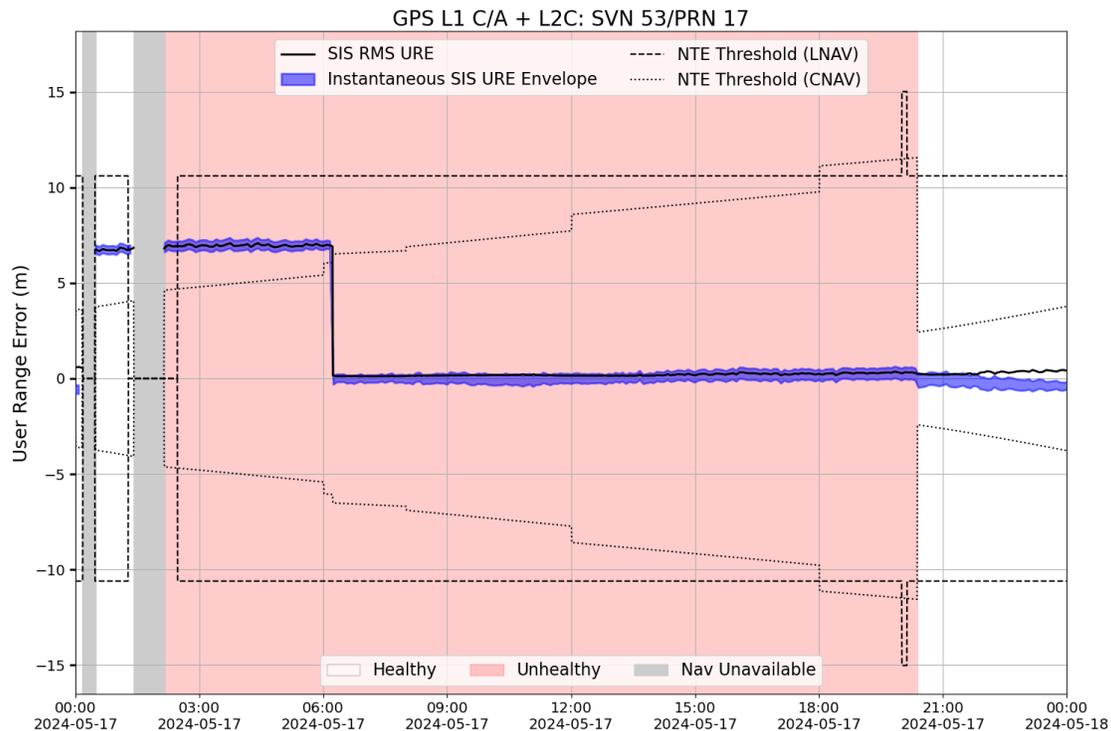


Figure A.4: Integrity Fault Event on 17 May 2024, SVN 53/PRN 17

A.6.2 25 May SVN 48/PRN 7 Event

On 25 May 2024, SVN 48/PRN 7 exceeded the LNAV and L2C CNAV NTE URE integrity thresholds. Figures A.5 and A.6 show the SIS RMS URE and the range of SIS instantaneous URE values for L1 C/A and L1 C/A + L2C, and 4.42 times the broadcast LNAV and L2C CNAV URA NTE thresholds for the period of interest. Note that the plot is on a log scale to show the range in the UREs. The shaded regions reflect L2C signal status.

Around 15:25 a rapid change in the satellite clock offset resulted in an increase in UREs. Due to differences in the broadcast URA terms for different signals, the maximum SIS instantaneous URE exceeded the LNAV NTE threshold at 15:47:00 and the L2C CNAV NTE threshold at 15:45:30, beginning the fault period. UREs continued to increase until the LNAV and L2C CNAV broadcasts ceased at 16:21:30 and 16:29:30, respectively, ending the event at durations of 34.5 and 44.0 minutes. The maximum SIS instantaneous URE during this period was 40.26 m for L1 C/A and 39.71 m for L1 C/A + L2C. The LNAV NTE threshold during the event was 10.608 m. The L2C CNAV NTE threshold ranged from 10.22 m at the start of the event to a maximum of 10.26 m, with a value of 2.95 m at the end of the event. Broadcast resumed on the satellite with an unhealthy indication at 18:28:00 for LNAV and at 17:42:00 for L2C CNAV. While not visible in the figure, the satellite remained unhealthy until 18:22:30 on 05 June 2024.

This satellite does not broadcast on L5. As a result, this event occurred on L1 C/A and L1 C/A + L2C.

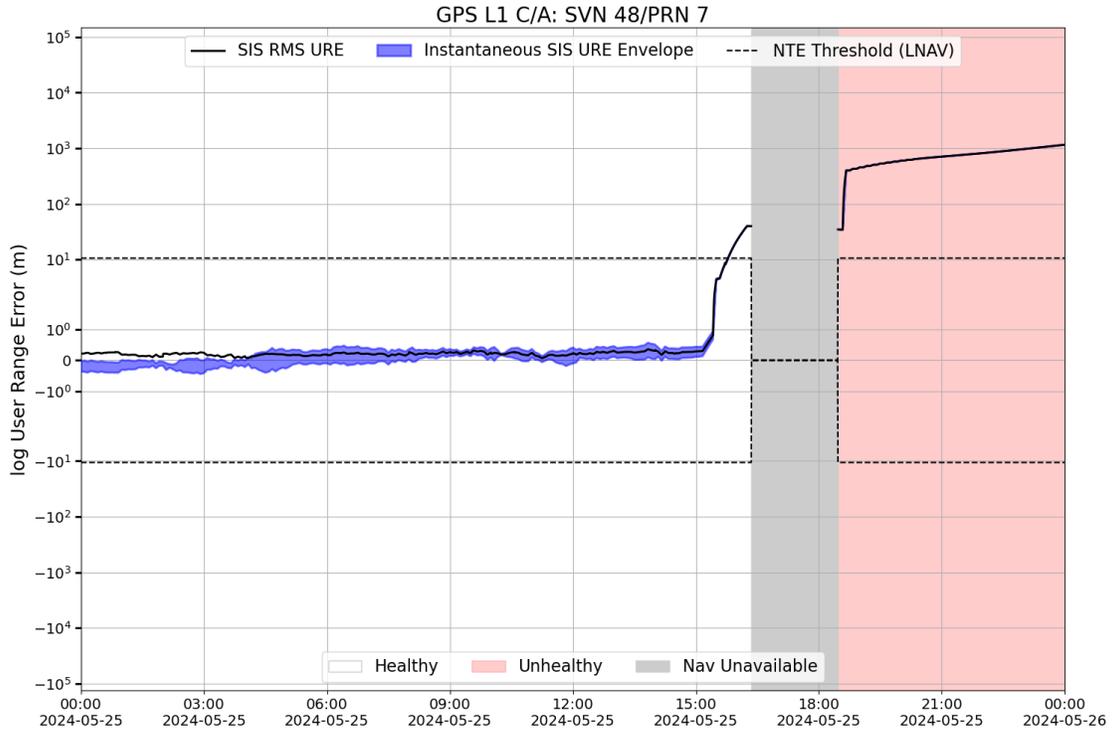


Figure A.5: Integrity Fault Event on L1 C/A, 25 May 2024, SVN 48/PRN 7

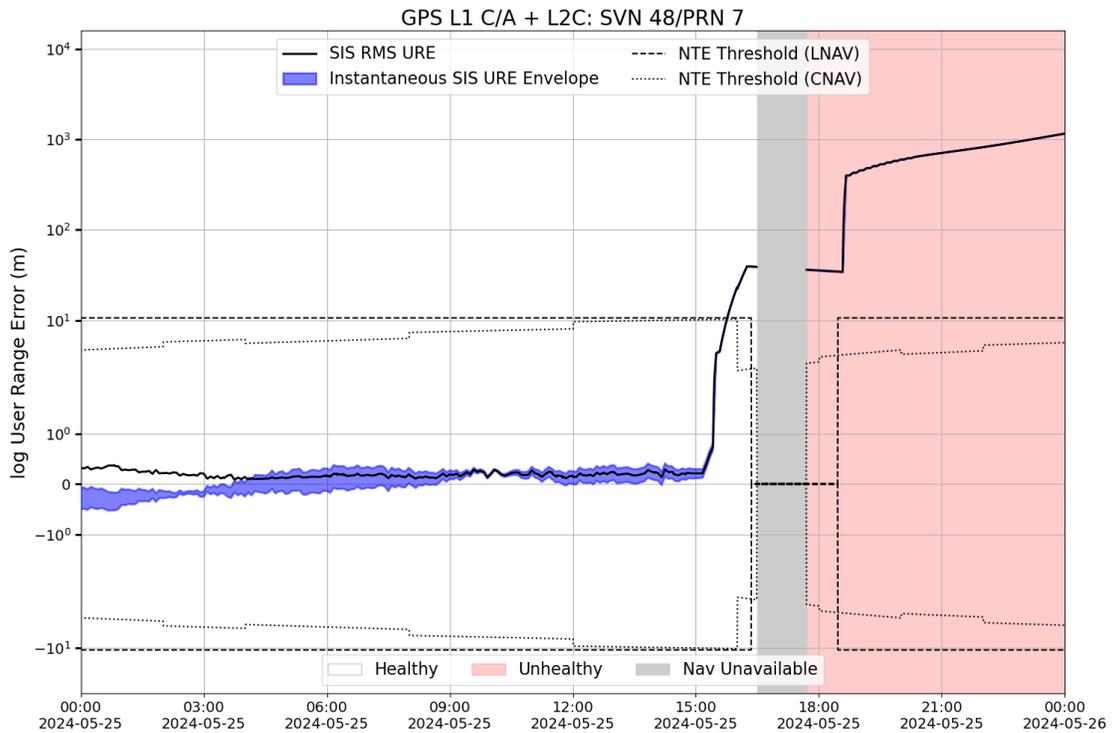


Figure A.6: Integrity Fault Event on L1 C/A + L2C, 25 May 2024, SVN 48/PRN 7

A.6.3 01 and 03 November SVN 71/PRN 26 Events

On 01 and 03 November 2024, SVN 71/PRN 26 exceeded both the L2C and L5 CNAV NTE URE threshold twice. Note that L5 is pre-operational and set unhealthy. Figure A.7 shows the SIS RMS URE and the range of SIS instantaneous URE values for L1 CA + L2C, and 4.42 times the broadcast LNAV and L2C CNAV URA NTE thresholds for the period of interest. Figure A.8 shows the corresponding values for L1 CA + L5Q.

Around 18:00 on 01 November, fluctuations in the satellite clock drift prompted a ramp increase in UREs. Multiple uploads over next two days made adjustments to both the broadcast clock offset and clock drift terms. However, during some periods, the URE exceeded the L2C and L5 CNAV NTE thresholds, resulting in two excursion events for L2C and L5Q. The satellite continued to broadcast available signals throughout this period. The LNAV NTE URE threshold during these excursion periods was either 10.608 m or 15.028 m. As a result, these events occurred only on L1 C/A + L2C and L1 C/A + L5Q.

The first event began on 01 November, with the maximum SIS instantaneous UREs exceeding the NTE threshold at 19:06:00 for L2C CNAV and at 19:10:00 for L5 CNAV. An upload at 19:27:00 for L2C and at 19:26:30 for L5 corrected the clock offset term and lowered the UREs back below the NTE threshold, ending the event at durations of 21.0 minutes and 16.5 minutes, respectively. The maximum SIS instantaneous URE during this period was 3.80 m on L1 C/A + L2C and 3.60 m on L1 C/A + L5Q. The CNAV NTE URE threshold ranged from 2.90 m to 3.03 m during the event.

The second event began on 03 November, with the maximum SIS instantaneous UREs exceeding the NTE threshold at 01:06:30 for L2C CNAV and at 01:17:00 for L5 CNAV. An upload at 01:29:00 for L2C and at 01:28:30 for L5 corrected the clock offset term and lowered the UREs back below the NTE threshold, ending the event at durations of 22.5 minutes and 11.5 minutes, respectively. The maximum SIS instantaneous URE during the period was 3.65 m on L1 C/A + L2C and 3.49 m on L1 C/A + L5Q. The CNAV NTE URE threshold ranged from 3.12 m to 3.26 m for the L2C event and from 3.18 m to 3.25 m for the L5 event. The satellite clock drift stabilized after this event.

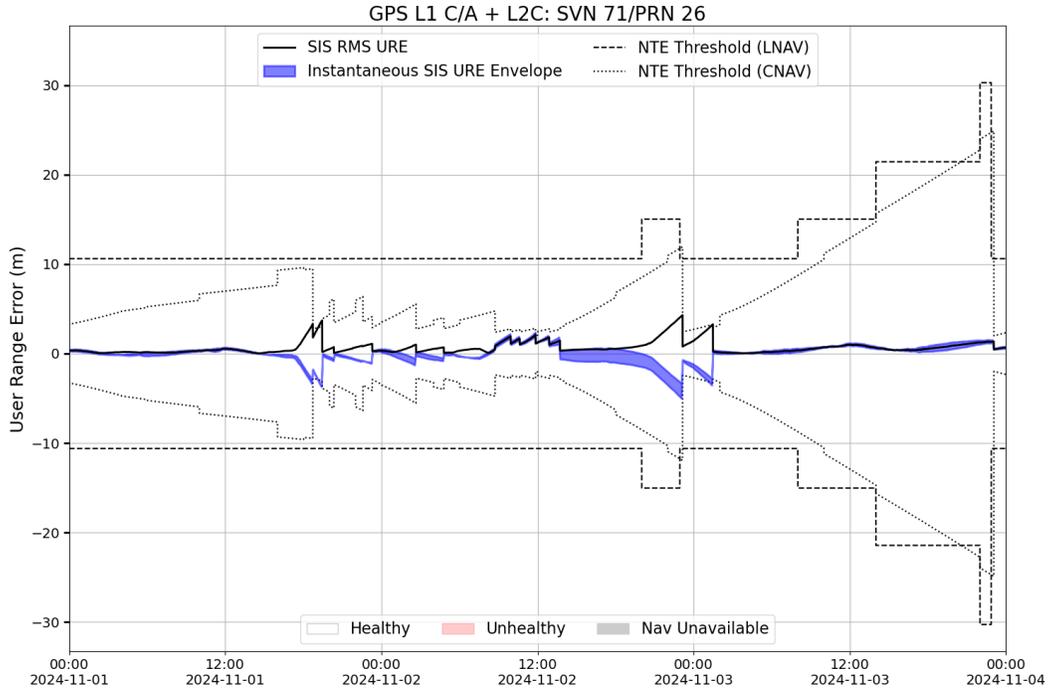


Figure A.7: Integrity Fault Events on L1 C/A + L2C, 01 and 03 November 2024, SVN 71/PRN 26

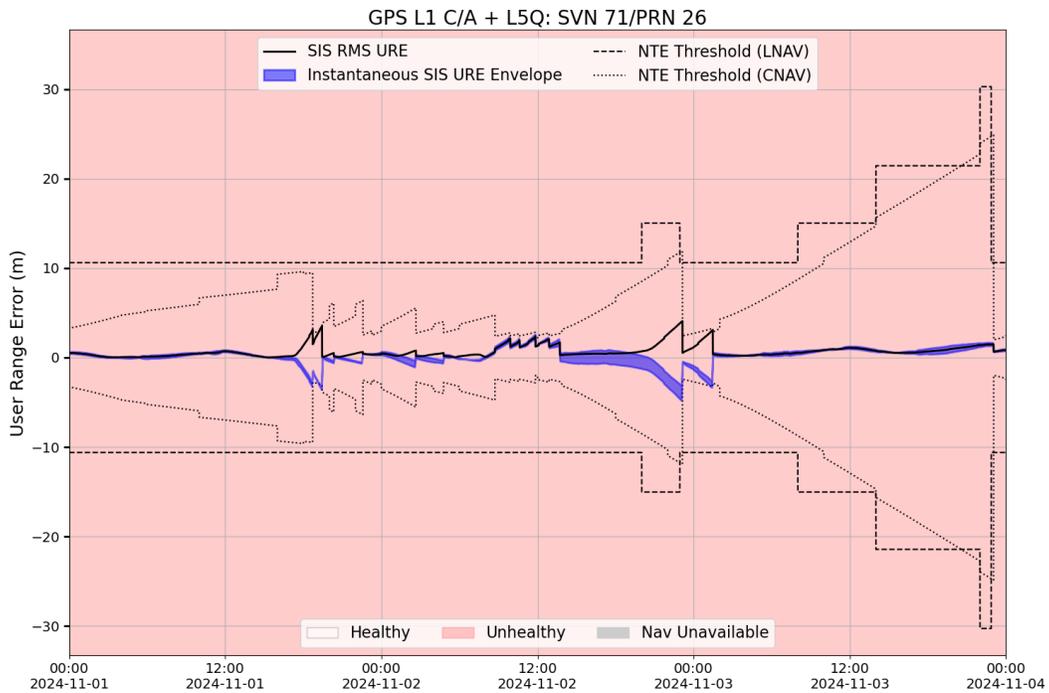


Figure A.8: Integrity Fault Events on L1 C/A + L5Q, 01 and 03 November 2024, SVN 71/PRN 26

A.7 Additional DOP Analysis

There are several ways to look at DOP values when various averaging techniques are taken into account. Assuming a set of DOP values, each identified by latitude (λ), longitude (θ), and time (t), then each individual value is represented by $DOP_{\lambda,\theta,t}$.

The global average DOP for a day, $\langle DOP \rangle(\text{day})$, is defined to be:

$$\langle DOP \rangle(\text{day}) = \frac{\sum_t \sum_\theta \sum_\lambda DOP_{\lambda,\theta,t}}{N_{\text{grid}} \times N_t}$$

Another measure of performance is the average DOP over the day at the worst site, $\langle DOP \rangle_{\text{worst site}}$. In this case, the average over a day is computed for each unique latitude/longitude combination and the worst average of the day is taken as the result.

$$\langle DOP \rangle_{\text{worst site}}(\text{day}) = \max_{\lambda,\theta} \left(\frac{\sum_t DOP_{\lambda,\theta,t}}{N_t} \right)$$

This statistic is the most closely related to the description of worst site used in Section 3.6.1.1.

The average of worst site DOP, $\langle DOP_{\text{worst site}} \rangle$, is calculated by obtaining the worst DOP in the latitude/longitude grid at each time, then averaging these values over the day.

$$\langle DOP_{\text{worst site}} \rangle(\text{day}) = \frac{\sum_t \max_{\lambda,\theta} (DOP_{\lambda,\theta,t})}{N_t}$$

Given that the $\langle DOP \rangle_{\text{worst site}}(\text{day})$ is most closely related to the worst site definition used in Section 3.6.1.1, this is the statistic that will be used for “worst site” in the remainder of this section. For 2024, both $\langle DOP \rangle_{\text{worst site}}(\text{day})$ and $\langle DOP_{\text{worst site}} \rangle(\text{day})$ satisfy the SPS PS 2020 assertions.

It is worth noting the following mathematical relationship between these quantities:

$$\langle DOP \rangle \leq \langle DOP \rangle_{\text{worst site}} \leq \langle DOP_{\text{worst site}} \rangle$$

In general, this relationship serves as a sanity check on the DOP results and establishes that these metrics are increasingly sensitive to outliers in $DOP_{\lambda,\theta,t}$.

In calculating the percentage of the time that the $\langle DOP \rangle$ and $\langle DOP \rangle_{\text{worst site}}$ are within bounds, several other statistics were calculated which provide insight into the availability of the GPS constellation throughout the world. Included in these statistics are the annual means of the daily global average DOP and the $\langle DOP \rangle_{\text{worst site}}$ values. These values are presented in Table A.6, with values for 2021 through 2023 provided for comparison.

The average number of satellites and the fewest satellites visible across the grid are calculated as part of the DOP calculations. Also shown in Table A.6 are the annual means of the global average number of satellites visible to grid cells on a 111 km \times 111 km (latitude by longitude) global grid and the annual means of the number of satellites in the worst-site grid cell (defined as seeing the fewest number of satellites). It should be noted that the worst site for each of these values was not only determined independently from day-to-day, but was also determined independently for each metric. That is to say, it is not guaranteed that the worst site with respect to Horizontal DOP (HDOP) is the same as the worst site with respect to PDOP. For all quantities shown in Table A.6, the values are very similar across all four years.

Table A.6: Additional DOP Annually-Averaged Visibility Statistics for 2021 – 2024

	$\langle \text{DOP} \rangle$				$\langle \text{DOP} \rangle_{\text{worst site}}$			
	2021	2022	2023	2024	2021	2022	2023	2024
Horizontal DOP	0.84	0.83	0.83	0.83	0.95	0.95	0.95	0.95
Vertical DOP	1.37	1.35	1.35	1.34	1.70	1.69	1.69	1.69
Time DOP	0.80	0.79	0.78	0.78	0.90	0.90	0.90	0.89
Position DOP	1.61	1.59	1.59	1.58	1.86	1.85	1.84	1.84
Geometry DOP	1.80	1.78	1.77	1.77	2.07	2.05	2.05	2.05
Number of visible SVs	10.25	10.32	10.41	10.43	5.89	5.95	5.83	6.00

There are a few other statistics that can add insight regarding the GPS system availability. The primary availability metric requires that the globally averaged PDOP be in-bounds at least 98% of the time. There are two related values: the number of days for which the PDOP is in bounds and the 98th percentile of the daily globally averaged PDOP values. Similarly, calculations can be done for $\langle \text{DOP} \rangle_{\text{worst site}}$ criteria of having the PDOP ≤ 6 greater than 88% of the time. Table A.7 presents these values for 2024 and the previous three years.

Table A.7: Additional PDOP Statistics

	2021	2022	2023	2024
% of Days with the $\langle \text{PDOP} \rangle \leq 6$	100.00	100.00	100.00	100.00
% of Days with the $\langle \text{PDOP} \rangle$ at Worst Site ≤ 6	100.00	100.00	100.00	100.00
98 th Percentile of $\langle \text{PDOP} \rangle$	1.69	1.64	1.65	1.63
88 th Percentile of $\langle \text{PDOP} \rangle_{\text{worst site}}$	1.90	1.86	1.87	1.88

Table A.7 shows that the average DOP values for 2024 are nearly identical to the previous three years.

Appendix B

Supporting Data

This chapter includes supporting data for the analysis, including PRN to SVN mapping, NANU activity, and SVN to Plane-Slot mapping.

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B.2 NANU Activity in 2024	95
B.3 SVN to Plane-Slot Mapping for 2024	98

B.1 PRN to SVN Mapping for 2024

Throughout the report, SVs have been referred to by both PRN and SVN. The PRN to SVN mapping is time dependent as PRN assignments change. The number of operational SVs is typically very close to the number of available PRNs. Therefore, it is useful to have a summary of the PRN to SVN mapping as a function of time. Figure B.1 presents that mapping for 2024. SVNs on the right vertical axis appear in the order in which they were assigned the PRN values in 2024. Colored bars indicate the range of time each relationship was in effect. Start and end times of relationships are indicated by the dates labeling each vertical line.

These data are assembled by ARL:UT from the NANUs and the operational advisories, and confirmed by discussion with The Aerospace Corporation staff supporting 2 NWS.

B.2 NANU Activity in 2024

Several sections in the report make use of NANUs. It is useful to have a time history of the relevant NANUs sorted by SVN. This makes it convenient to determine which NANU(s) should be examined if an anomaly is observed for a particular satellite at a particular time.

Figure B.2 presents a plot of the NANU activity in 2024. Blue bars represent scheduled outages and red bars represent unscheduled outages. Gray bars represent SVs that were decommissioned in 2024. Light green bars represent SVs after launch prior to a NANU declaring initial usability. NANU numbers are indicated next to each bar. In the event there is more than one NANU for an outage, the last NANU number is displayed.

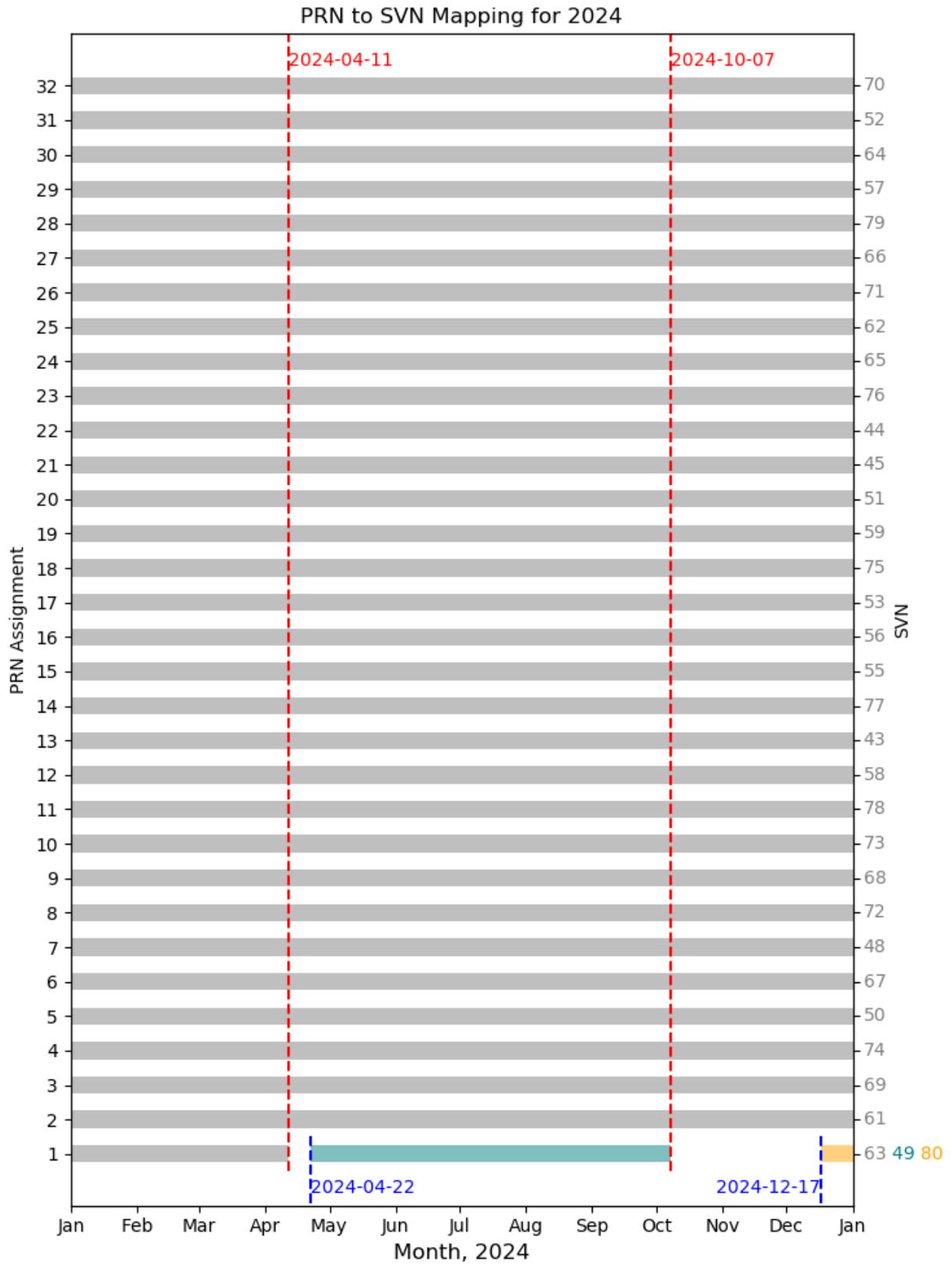


Figure B.1: PRN to SVN Mapping for 2024

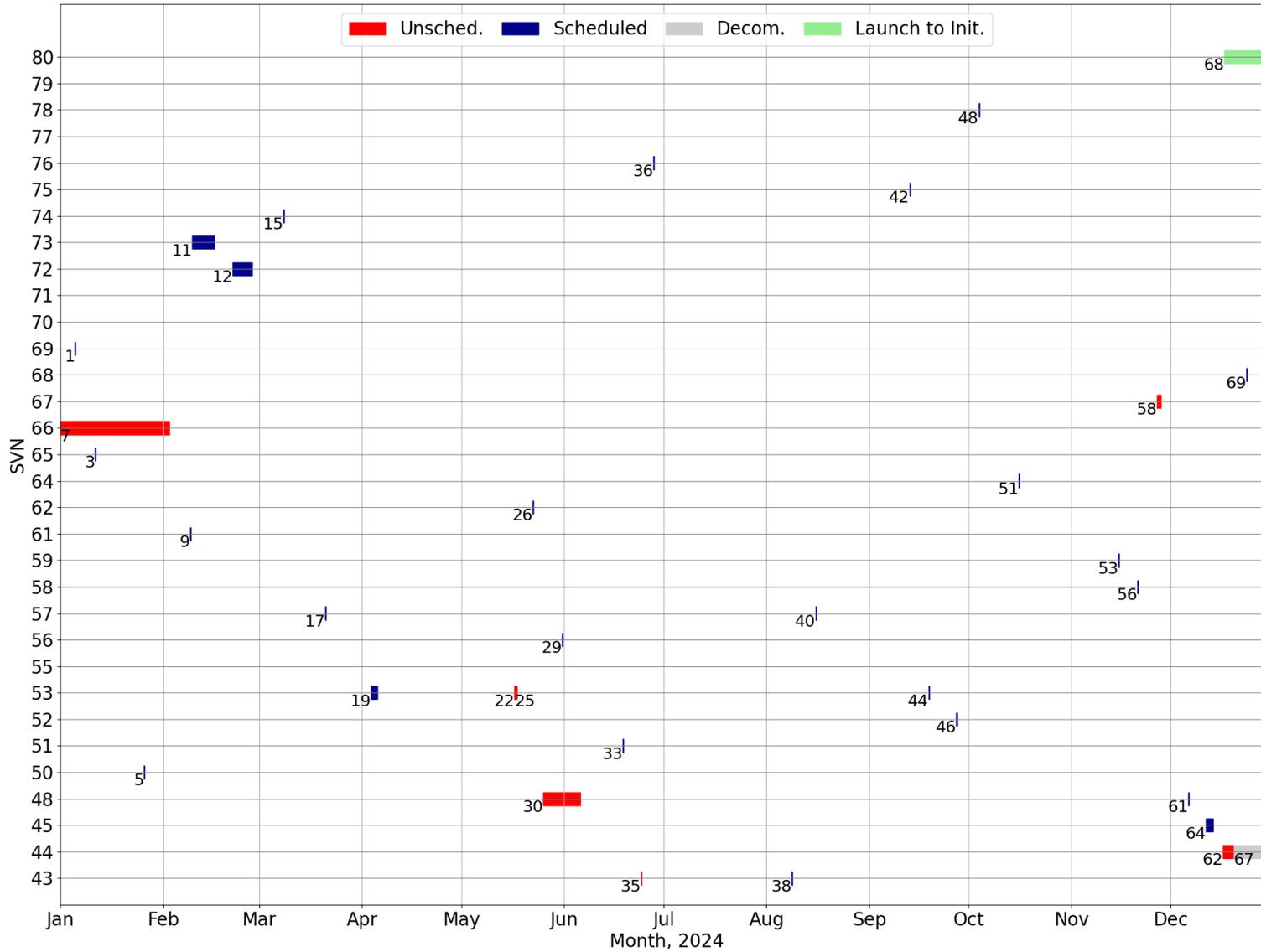


Figure B.2: Plot of NANU Activity for 2024

B.3 SVN to Plane-Slot Mapping for 2024

Several assertions utilize the plane-slot arrangement specified in the SPS PS 2020. Evaluation of these assertions requires information on the plane-slot occupancy during the year. Six planes (A-F) are defined. Each plane contains four slots (1-4). For each plane, one slot may be expanded into a pair of locations designated by F (fore) or A (aft). The possible plane-slot designators appear on the vertical axis of Figure B.3.

The constellation definition in Section 3.2 of the SPS PS 2020 that provides the plane-slot definitions is an ideal model in the sense that it assumes all SVs have zero eccentricity and nominal inclination. Slots within a plane are defined in terms of the Right Ascension of the Ascending Node (RAAN) and the Argument of Latitude of a hypothetical nominal satellite at a specified epoch. Appendix A.2.4 of the SPS PS 2020 defines how to propagate these nominal slot centers in time. Appendix A.7.4 of the SPS PS 2020 defines a slot as occupied when the footprint of a satellite (or combined footprint of a pair of satellites, for expanded slots) on the surface of the Earth overlaps at least 95% of the nominal slot's footprint, averaged over an orbit revolution, and provides an inequality in terms of RAAN and Argument of Latitude offset as a conservative approximation of the 95% footprint overlap condition.

Information on plane-slot assignment appears in the operational advisory (OA) provided by 2 NWS to the U.S. Coast Guard (USCG) Navigation Center, defined in ICD-GPS-240. However, the format does not permit clarity for expanded slots: there is no provision for fore or aft designations. Also, OA designations for slots contain numbers beyond the slots defined in the performance standard. The operators define these “slots of convenience” without fixed meaning for constellation position. As a result, OA interpretation can be challenging. During 2024, the Navigation Center also posted a graphic depicting the SV locations in terms of plane and slot. This graphic shows the status at a particular epoch.

As satellites are moved within the constellation, there exist periods when more than one SV may be present within the defined boundaries of a slot. From the user's point of view, the slot should be counted as occupied if a satellite transmitting a healthy signal, or a combination of multiple satellites each transmitting a healthy signal, cover the area visible from the designated primary slot locations. Additionally, Appendix A.7.2.4 and Appendix A.7.2.5 of the SPS PS 2020 define “equivalent-or-better” non-standard configurations of expanded slots which meet the 95% overlap condition but may not have the nominal fore or aft slots themselves meet the individual overlap conditions. These circumstances require particular care to properly determine plane-slot assignments.

Figure B.3 presents a plot of the plane-slot relationships throughout 2024, including start and end dates of slot occupancy. The contents of Figure B.3 are determined by assessing the 95% footprint overlap criterion for the actual satellite positions as compared to the nominal constellation. Refer to Appendix C.6 for more information on this process. In the cases where an SV is decommissioned or a new SV is launched, the appropriate NANUs were also checked to confirm dates. The dates when satellites are judged to be present in a slot location are noted only when a change occurs in the plane-slot during the year. This allows the reader to determine when multiple satellites occupied the same slot.

For 2024, no satellites changed plane-slot location.

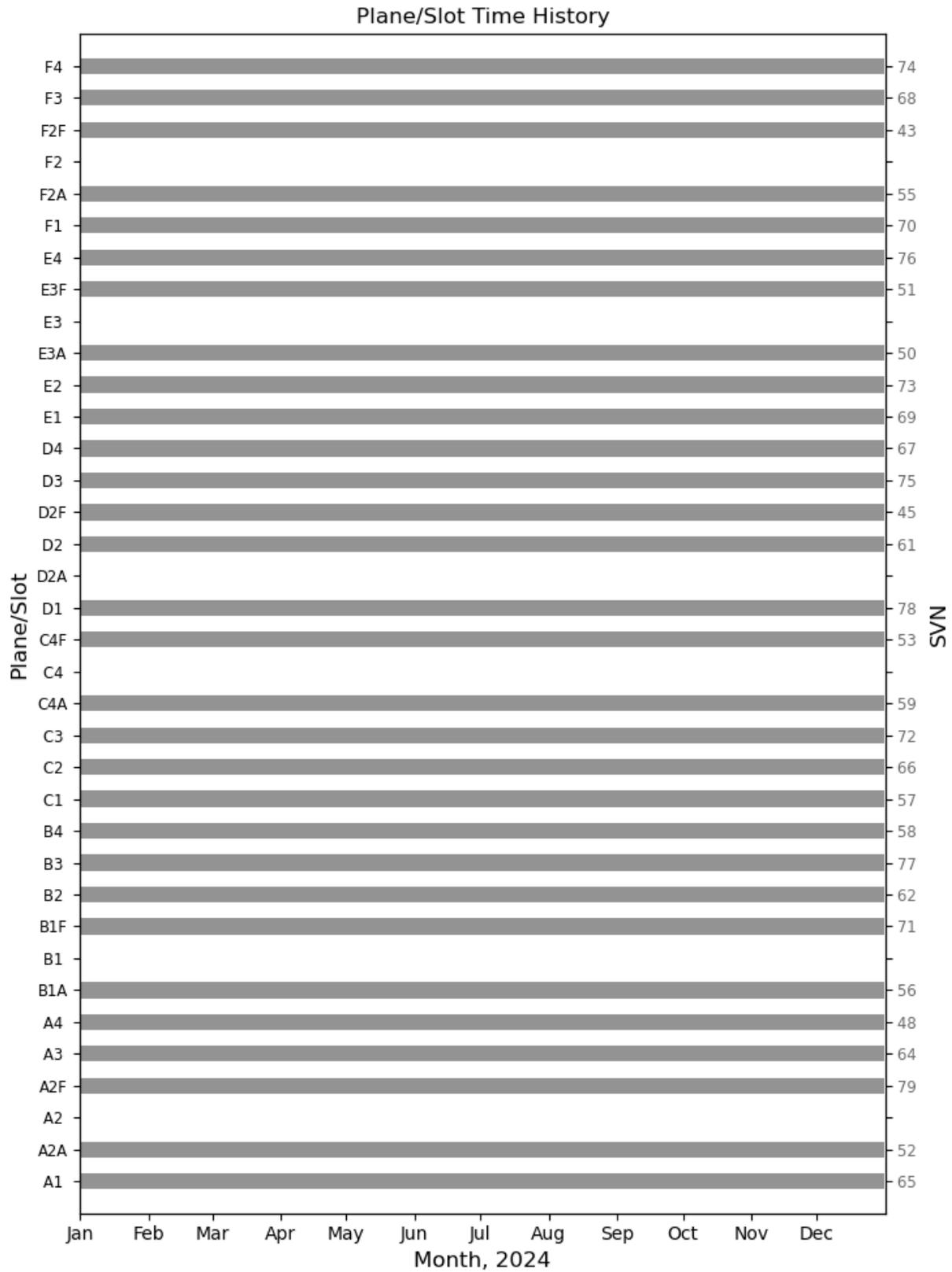


Figure B.3: Time History of Satellite Plane-Slots for 2024

Appendix C

Analysis Details

This chapter provides details on the analysis process. Topics include the motivation behind selected signal combinations, the methodology of the URE process, the process by which navigation message data are selected, the means by which AOD is computed, and the determination of plane-slot assignments.

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C.1 Signals Used

The signals and signal combinations defined in the SPS PS 2020 are listed in Table 1.1 and replicated below. While it is possible to generate results to test all assertions directly, this would result in a large duplication of effort. Instead, what is necessary is to cover the signals of interest and the navigation messages of interest. If no assertion violations are found for such a subset, then assertions for the other signal combinations can be assumed to be satisfied. However, if any violation of assertions is detected within this subset, it may be necessary to compute results for additional signal combinations to verify the results.

Table C.1: SPS SIS Signal Combinations Covered by SPS PS 2020

One Carrier Single Frequency (SF)	Two Carriers Dual Frequency (DF)	Three Carriers Triple Frequency (TF)
C/A-code + LNAV Data	(C/A + CM)-codes + CNAV Data	(C/A + CM + I5)-codes + CNAV Data
CM-code + CNAV Data	(C/A + CL)-codes + CNAV Data	(C/A + CL + I5)-codes + CNAV Data
CL-code + CNAV Data	(C/A + CM+CL)-codes + CNAV Data	(C/A + CM+CL + I5)-codes + CNAV Data
(CM+CL)-codes + CNAV Data	(C/A + I5)-codes + CNAV Data	(C/A + CM + Q5)-codes + CNAV Data
I5-code + CNAV Data	(C/A + Q5)-codes + CNAV Data	(C/A + CL + Q5)-codes + CNAV Data
Q5-code + CNAV Data	(C/A + I5+Q5)-codes + CNAV Data	(C/A + CM+CL + Q5)-codes + CNAV Data
(I5+Q5)-codes + CNAV Data		(C/A + CM+CL + I5+Q5)-codes + CNAV Data

The signal combinations selected for evaluation are summarized in Table C.2. This selection of signal combinations includes all unique signals at least once and all navigation messages (LNAV, CNAV-L2C, CNAV-L5I). Table C.2 notes whether or not T_{GD} and ISC values are included in the URE computation.

Table C.2: Rationale for Selection of Signal Combinations

Signal Combination	Navigation Message	Rationale	T_{GD}	ISC
L1 C/A	LNAV	Primary SPS signal; checks L1 C/A and LNAV	✓	✗
L1 C/A + L2C	CNAV from L2C	SPS dual-frequency combination; checks L2C CNAV message	✓	✓
L1 C/A + L5Q	CNAV from L5I	SPS dual-frequency combination; checks L5I CNAV message	✓	✓

C.2 URE Methodology

User range error (URE) represents the accuracy of the broadcast navigation messages. URE values are central to several of the assertions evaluated in this report. The concept of URE is simple, but the execution is dependent on many details. This section provides an overview of the methodology used in determining URE values.

The URE statistics presented in this report are based on a comparison of the BC&P against the PC&P. This is a useful approach, but one that has specific limitations. The most significant limitation is that the PC&P may not capture the effect of individual discontinuities or large effects over short time scales (e.g., a frequency step or clock run-off). Nonetheless, this approach is appropriate given the 30-day period of averaging implemented in determining URE compared to brief (less than an hour) periods of the rare discontinuities. Briefly, this approach allows the computation of URE *without direct reference to observations* from any particular ground sites, though the PC&P carries an implicit network dependency based on the set of ground stations used to derive the precise orbits from which the PC&P is derived.

Throughout this report, there are references to several distinct SIS URE expressions. Each of these SIS URE expressions means something slightly different. It is important to pay careful attention to the particular SIS URE expression being used in each case to avoid misinterpreting the associated results.

Throughout this section, there are references to the “Instantaneous SIS RMS URE.” This is a statistical basis SIS URE (note the “RMS” statistical qualifier), where the measurement quantity is the instantaneous SIS URE, and the span of the statistic covers that one particular point (“instant”) in time across a large range of spatial points. This is effectively the evaluation of the instantaneous SIS URE across every spatial point in the area of the service volume visible to the SV at that particular instant in time.

Put another way, consider the signal from a given SV at a given point in time. That signal intersects the surface of the Earth over an area, and at each point in that area there is a unique instantaneous SIS URE value based on geometric relationship between the SV and the point of interest. In the name “Instantaneous SIS RMS URE,” the “Instantaneous” means that no time averaging occurs. The “RMS” refers to taking the RMS of all the individual instantaneous SIS URE values across the area visible to the SV for a single time. This concept is explained in SPS PS 2020 Section A.4.11, and the relevant equation is presented in Appendix C.2.4 of this report.

Appendix A.4.11 of the SPS PS 2020 defines two types of SIS URE values:

- Instantaneous SIS URE values which express the URE at a given moment along a specific line of sight, and
- Statistical SIS URE values which express the URE across the SV field of view for a time period.

The instantaneous SIS URE values are most useful for describing the largest errors in the field of view from the SV or to establish the URE to a particular user at a particular point in time. The Statistical SIS URE values allow discussion of the overall accuracy across the entire field of view at a given point in time or over a period in time.

When the BC&P and PC&P are used to estimate the range residual along a satellite-to-receiver line-of-sight vector at a given instant in time, the result is an instantaneous SIS URE. Some of the primary differences between instantaneous SIS UREs and Statistical SIS UREs are given in Table C.3.

Table C.3: Characteristics of SIS URE Methods

Instantaneous SIS URE	Statistical SIS URE
Always algebraically signed (\pm) number	Never algebraically signed
Never a statistical qualifier	Always a statistical qualifier (RMS, 95%, etc.)
Specific to a particular time and place	Statistic over span of times, or places, or both

C.2.1 Clock and Position Values for Broadcast and Precise

The BC&P values used in this report are derived from multiple GPS navigation messages (see Table C.2). This verifies that all available navigation message data sets fulfill the relevant assertions.

The broadcast navigation message data were collected by the National Geospatial-Intelligence Agency (NGA) GPS Monitor Station Network (MSN) (see Section C.3). The message data provide a set of parameters that are used in conjunction with equations in the signal interface specifications [2], [3] to derive the SV position and clock offset at a given time. The signal interface specifications and the data allow the user to determine the period of time for which the data are valid. Our process evaluates the parameters at either a 30 s or 1 min cadence depending on the process. In all cases, our processes use the most recently transmitted navigation message in order to best replicate the user experience.

The PC&P values used in this report are derived from the NGA antenna phase center (APC) precise ephemeris (PE). This PE product is available from the NGA public website [13]. We use the APC version, as opposed to the center of mass (COM) version, due to the fact that both the GPS LNAV/CNAV messages and the NGA APC precise orbits are referenced to the L1 P(Y) + L2 P(Y) phase center for both orbit and clock. This removes the need to use antenna phase offset data to move the PC&P positions from the COM to the APC.

The NGA PE products are synchronized with GPS system time based on coordination with the GPS MCS. This is another advantage of the NGA PE products in that it minimizes the need to solve for a system time bias between the BC&P and the PC&P.

The NGA product is published in tabular SP3 format, with positions and clocks provided at a 5 min cadence. Lagrange interpolation is used for calculating SV position, using the five points prior to and after the desired epoch. Linear interpolation is used for the clock values.

C.2.2 ISCs and DCBs

When computing UREs from signal combinations other than the primary signal combination, it is necessary to account for the effective phase center differences between each. The primary signal combination is the combination from which the BC&P and PC&P were derived. In this case, L1 P(Y) + L2 P(Y) is the primary signal combination.

The differences cause range errors that manifest as clock errors. These differences are quantified in the broadcast inter-signal correction (ISC) values. The interface specifications provide equations for adjusting the pseudorange values such that they appear to have been collected from the phase center of the primary signal combination.

A result of this process is that any errors in a given broadcast ISC value will be reflected in pseudoranges for all signal combinations to which that ISC value applies. (For the purpose of this section, the T_{GD} is regarded as an additional ISC value). The extent to which the errors affect the result will vary based on scale factors related to the frequencies involved. These effects must be accounted for when UREs are evaluated.

The broadcast ISC values are typically updated no more than four times a year. The updates are not aligned with quarters and are only approximately spaced. Few SVs are updated each quarter and several do not require updates for over a year. Therefore, the ISC values are constant over long periods.

The URE process may mitigate ISC errors in the following manner¹:

- Compute the SV position and clock error at a given moment using both the broadcast orbit and the NGA PE.
- Adjust the clock error derived from the broadcast orbit from the phase center of the primary signal combination to the phase center of the signal combination of interest using the inverse of the process defined in the interface specification.
- Adjust the clock error derived from the precise orbit in a similar manner, but using a source of ISC post-processed estimates.
- Continue with the regular URE evaluation process using the adjusted clock errors.

Note the reliance on ISC post-processed values. The evaluation of ISC values is a challenging task. The quantity of interest is not directly observable. As a result, the calculation typically requires a large amount of data and some assumptions. For example, some ISC calculations assume a zero-mean error across the constellation. This is likely not the case, but it is assumed common errors will be removed from the process.

There are several organizations within the IGS that regularly evaluate the ISC values (described as differential code bias (DCB) values). For the remainder of this section, the DCB values produced by DLR (German Aerospace Center) will be considered. This choice is based on the fact that there is a paper describing how the DCB values are derived [14].

¹This process differs from the process used prior to 2020. The earlier process used constant factors that were applied across all the results in an RSS fashion.

In 2021 [15] and 2022 [16], the IGS provided updated guidance on how DCB are to be calculated. The change meant DCBs and the antenna phase center (APC) offset corrections (PCO) are handled separately. Until 27 November 2022, the DLR DCB combined these two terms. From that date forward the PCO adjustment has been removed from the DCB values. The change meant the PCOs are considered as an additional component to the clock.

This is done through use of the standard dual-frequency correction equation:

$$PCO = (f_1^2 PCO_{z,f_1} - f_2^2 PCO_{z,f_2}) / (f_1^2 - f_2^2)$$

Where:

- f_1 is the first frequency
- f_2 is the second frequency
- PCO_{z,f_1} is the PCO at f_1
- PCO_{z,f_2} is the PCO at f_2

Table C.4 is a summary of the ISC accounting process. Table C.4 is organized in a manner similar to Table 3 of Montenbruck (2018) [17]. Table C.4 contains the same GPS signal combinations but is expanded to include the other signal combinations of interest.

Table C.4: GPS Signal Combinations of Interest and Orbit Adjustments

Msg.	Signals	BC&P Correction to Clock Error	PC&P Correction to Clock Error
LNAV	L1 P(Y) + L2 P(Y)	0	0
	L1 P(Y)	T_{GD}	$-\gamma_{L2L1} DCB_{C1W-C2W}$
	L1 C/A	T_{GD}	$-\gamma_{L2L1} DCB_{C1W-C2W} + DCB_{C1C-C1W}$
CNAV	L1 C/A	$T_{GD} - ISC_{L1CA}$	$-\gamma_{L2L1} DCB_{C1W-C2W} + DCB_{C1C-C1W}$
	L1 C/A + L2C	$T_{GD} - \gamma_{L1L2} ISC_{L1CA} + \gamma_{L2L1} ISC_{L2C}$	$\gamma_{L1L2} DCB_{C1C-C1W} - \gamma_{L2L1} DCB_{C2L-C2W}$
	L1 C/A + L5Q	$T_{GD} - \gamma_{L1L5} ISC_{L1CA} + \gamma_{L5L1} ISC_{L5Q}$	$\gamma_{L1L5} DCB_{C1W-C2W} - \gamma_{L1L5} DCB_{C1C-C5Q}$

Where:

$$\begin{aligned} \gamma_{L1L2} &= f_{L1}^2 / (f_{L1}^2 - f_{L2}^2), \\ \gamma_{L2L1} &= f_{L2}^2 / (f_{L1}^2 - f_{L2}^2), \\ \gamma_{L1L5} &= f_{L1}^2 / (f_{L1}^2 - f_{L5}^2), \text{ and} \\ \gamma_{L5L1} &= f_{L5}^2 / (f_{L1}^2 - f_{L5}^2). \end{aligned}$$

Note that the first row of Table C.4 has zero for both values. This row represents the primary signal combination for GPS. The equations in the column labeled “BC&P Correction to Clock Error” are in IS-GPS-200 and IS-GPS-705.

There are some matters to consider when looking at the DLR DCB values:

- The DLR DCB data set contains the following values: C1C-C1W, C1C-C2W, C2W-C2S, C2W-C2L, C2W-C2X, C1C-C5Q, C1C-C5X, C1C-C1L, C1C-C1X. The names use RINEX signal nomenclature. As expected, there are no DCBs based on Y-code. However, the data set does contain DCBs based on codeless tracking (i.e., C1W and C2W). (The X suffix refers to combined signal tracking: e.g., C2M/C2L or L5I/L5Q).

- In addition, the list does not include all the needed DCBs. For example, there is no C1W-C5I (L1 codeless to L5I). If we assume both transitive and associative properties hold for DCB values, then some of the missing combinations may be derived. However, this also means the noise of DCBs so combined will be conflated.
- DLR produces both one-day and seven-day DCB values. These are usually published one to two months after the end of each quarter. Unless there are changes in the signal generation chain, the ISCs should be reasonably stable. However, the seven-day DCB values do shift from week to week. Frequently, shifts are aligned with SV outages or other changes in the composition of the SVs used in the derivation. This is an unfortunate side effect of the estimation process.
- The DCB values are derived including a zero-mean assumption. The GPS T_{GD} values are also biased in that any common group delay across the constellation is handled in the GPS system time estimate. However, there is no way of knowing the actual bias in either case.

The various biases are addressed in a two-step process:

- The first step is to compute the average bias between the BC&P correction and the PC&P correction across all SVs for the day. The PC&P corrections are then adjusted by this value to roughly overlay the BC&P corrections. There will still be non-zero variations between individual SVs.
- The second step is to remove the common clock bias across the SVs at each epoch. This addresses the remaining bias between the zero-mean assumptions.
- This process allows us to observe any large errors in the ISC values, however, the scale factor on the ISC and DCB values places a limit on the observability of the differences.
 - For the T_{GD} , the least significant bit (lsb) scale factor is 0.5 nsec (15 cm).
 - For the remaining ISC values, the scale factor is 0.029 nsec (0.9 cm).
 - The standard deviation on the DCBs is in the range 0.01 – 0.10 nsec (0.3 – 3 cm).
- Note that the GPS ISC values change infrequently (typically no more often than every three months) and we are using the 7-day average DCB values. Therefore, the ISC values and the DCB values will be constant for a given SV for a given day. As a result, the BC&P correction term and the PC&P correction term will be constant across a day but biased differently.
- Note that all this is done without reference to actual observations. If the ISC values and the DCB values were perfectly correct, the adjustments would cancel and the UREs for any signal-combination would be identical to the L1 P(Y) + L2 P(Y) URE values. Any differences are due to the relative errors in the ISC and DCB values.

C.2.3 Definition of 95th Percentile Global Statistic

Where the SPS PS 2020 uses the term “95th% Global Statistic” and the assertion includes a time period, it is interpreted to mean the description of “Brute Force 95th%” in SPS PS 2020 Appendix A.4.11 extended over time, as suggested by Note 1 in the same section. This is different than the interpretation of the phrase “95th% Global Average” from the SPS PS 2008. The interpretation of that term is discussed in C.2.4. The instantaneous SIS URE value is calculated for a large number of locations for each time in a series of times. The 95th percentile value is then selected from the entire set.

For each SV, this is done for a series of time points at a 5 min cadence. At each time point, the components of the URE (i.e., the radial, along-track, cross-track, and clock offset errors) are projected along the line of sight to each location to form a SIS instantaneous URE value. The collection of SIS instantaneous URE values at each time point are stored. Once the values for all the time points for a month have been computed, the absolute values of SIS instantaneous URE values for all time points are gathered together in a monthly set. The 95th percentile value is selected from that set.

This method uses an approximation of an equidistant grid over the portion of the Earth visible to the SV with a spacing of roughly 550 km (5° latitude on the surface of the Earth). Considering those points at or above a 5° elevation angle with respect to the SV, this yields a set of 596 SIS instantaneous URE values for each SV for each evaluation time. Figure C.1 illustrates this set of grid points for a particular SV-time shown as a projection onto the surface of the Earth.

This was done at a cadence of 5 min for each SV for all of 2024, and all 596 values were stored for all time points. Sets of values corresponding to each month were extracted (approximately 5 million values per SV-month). The absolute values and 95th percentile values for each month were selected as the result for the SV-month. This is the basis for Table 3.1.

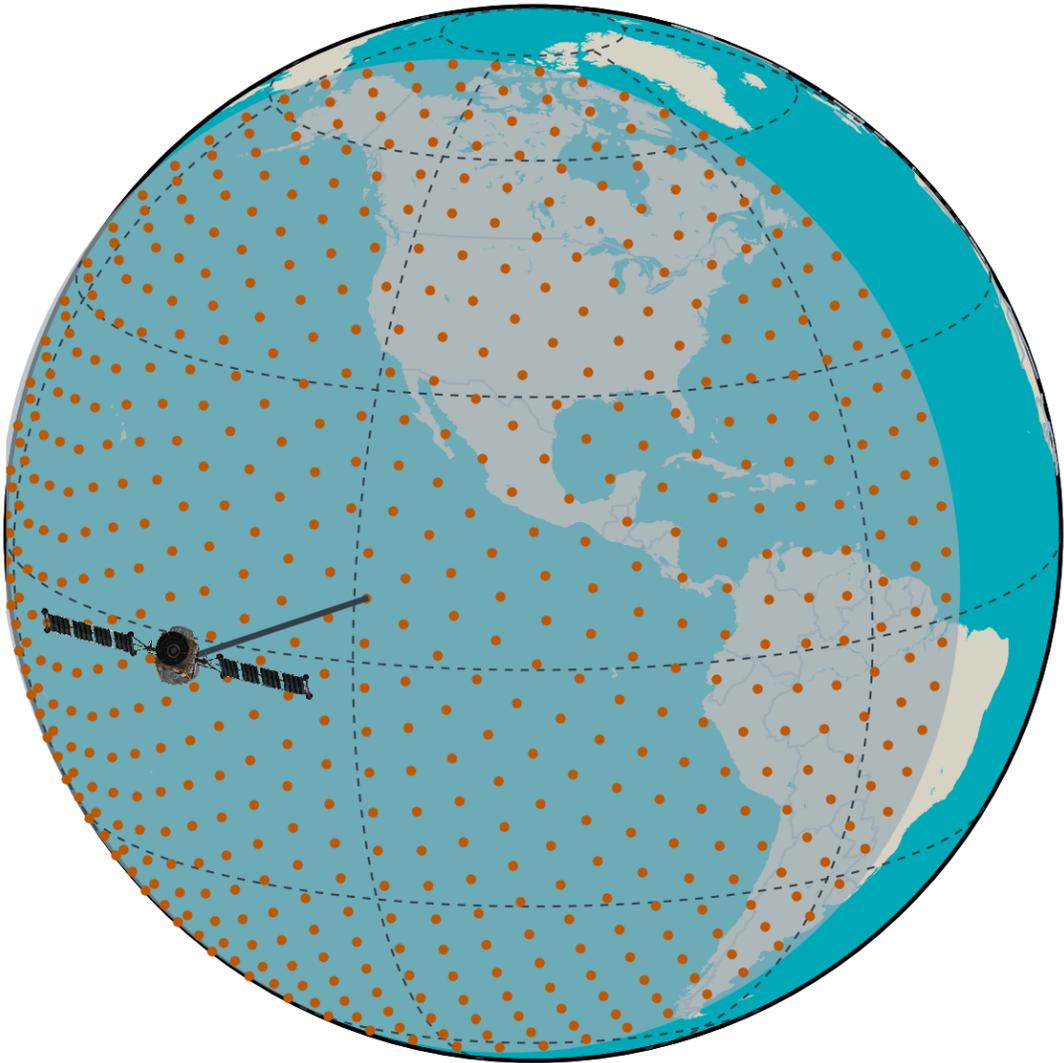


Figure C.1: Illustration of Grid Points for Global Statistic URE Computation

C.2.4 Definition of 95th Percentile Global Average

Where the SPS PS 2008 uses the term “95th% Global Average” and the assertions includes a time period, it is interpreted to mean a two-part process in which:

1. the description of “Piecewise RMS” in SPS PS 2008 Appendix A.4.11 is applied to obtain the instantaneous SIS RMS URE at a series of time points, then
2. the 95th percentile of the collection of instantaneous SIS RMS URE values is selected as the statistic.

This is different than the interpretation of the phrase “95th% Global Statistic” from SPS PS 2020. The interpretation of that term is discussed in C.2.3. The first part of the process is illustrated in Figure C.2.

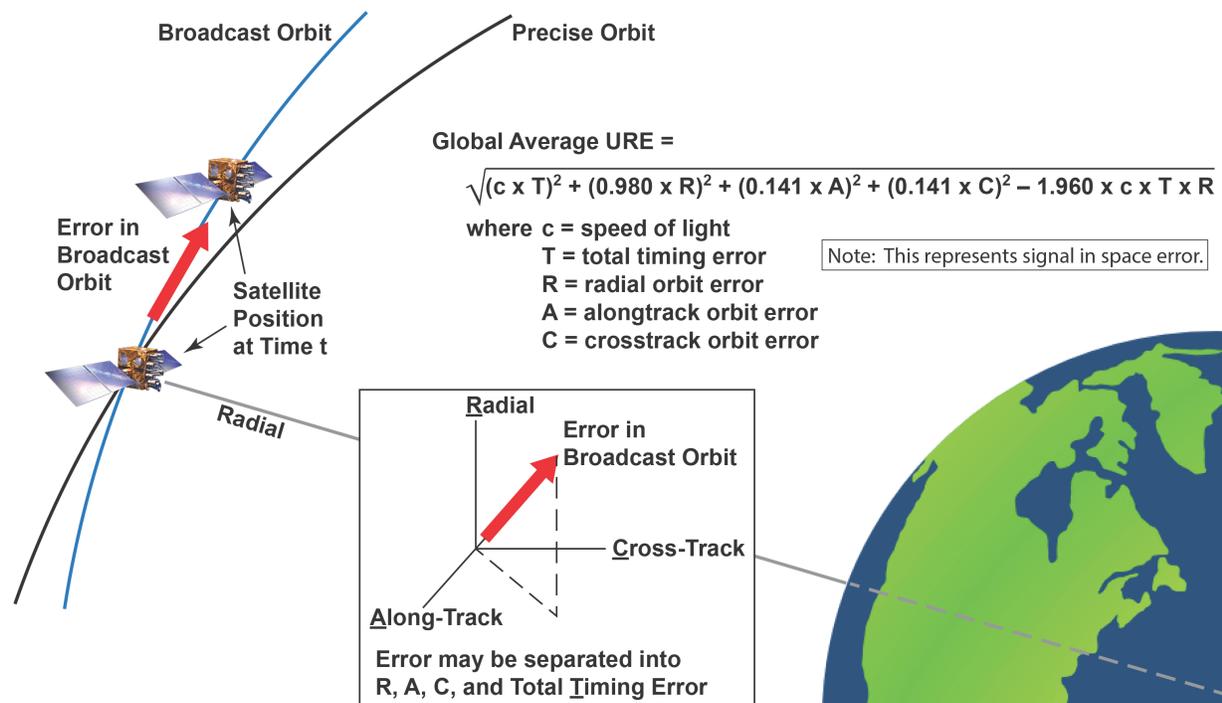


Figure C.2: Global Average URE as defined in SPS PS 2008

The equation shown in Figure C.2 is Equation A-1 of SPS PS 2008 Section A.4.11. The derivation for the generalized form of this equation can be found in the referenced paper [18]. This expression allows the computation of the URE from known errors. Based on the coefficients of this equation, the URE is calculated for a surface corresponding to the mean curvature of WGS 84.

For purposes of this report, the instantaneous SIS RMS URE values were generated at 30 s intervals for all of 2024. The URE was formed by differencing the BC&P and PC&P to obtain the radial, along-track, cross-track, and time errors at each epoch. These errors were used as inputs to the SPS PS 2008 Equation A-1.

After the instantaneous SIS RMS URE values were computed, values for periods when each SV was unhealthy or not broadcasting were discarded. The remaining values were then grouped by monthly period for each SV and sorted; the 95th percentile values within a given month were identified for each SV. The monthly grouping corresponds closely to the 30-day period suggested in Note 2 of SPS PS 2020 Section 3.4, while being more intuitive to the reader.

C.2.5 Limitations of URE Analysis

The methods described above work well when the estimated URE accuracy is below the required thresholds, as it verifies that the system is operating as expected. However, experience has shown that when an actual problem arises, the use of these procedures, without other cross-checking mechanisms, can create some issues and may lead to incorrect results. Consider the following two cases:

- The precision with which we can identify the time at which the URE values for an SV exceed a given threshold is limited by the cadence at which the UREs are calculated. We use a cadence of 30 s for the method described in Section C.2.4, which is a satisfactory granularity for nearly all cases. We use a cadence of 5 min for the method described in Section C.2.3, which may require additional examination of the results to determine the 30 s epoch at which a threshold was exceeded.
- When an SV is set unhealthy or cannot be tracked, the PC&P may provide misleading results. There are several options for handling discontinuities that occur during outages, which are implemented by the creators of the PC&P. Therefore, the URE values generated near such events may be incorrect. As a result, it is necessary to avoid accepting UREs into the statistical process under conditions in which the SV could not be tracked or was set unhealthy. This has been done for all the results presented here.

In all cases, when an apparent violation of the URE limit is encountered, we chose to reconcile the analysis described above with the behavior of ORDs formed from the data collected at NGA and IGS sites. Because the observational data used is collected at a 30 s cadence, we obtain a much higher resolution insight into the details of the actual event than we do with the interpolated PC&P.

C.2.6 Challenges of Comparing UREs Between Signal Combinations

The reader may expect that some signal combinations will have lower URE values than others for a variety of reasons. For example, a L1 C/A user using CNAV data has access to both T_{GD} and ISC values; whereas, a L1 C/A user using LNAV data has only T_{GD} .

However, such an expectation contains several hidden assumptions:

- If the T_{GD} and ISC values were perfect, the UREs would be identical for all signal combinations. However, the T_{GD} and ISC values contain errors, some of which are likely systematic while others are SV-dependent.
- The post-processed values which are used to check the T_{GD} and ISC values (see Appendix C.2.2) are also the result of an analysis process that yields less-than-perfect results.
- The broadcast orbits are derived from a large state estimator that considers a variety of factors. As a result, while the collection of UREs across the constellation for a given month will have a mean close to zero, the mean for a given SV over a month will be non-zero.

When all these error sources are combined, they add and cancel in a manner that may lead to non-intuitive results. Therefore, some signal-combinations may have URE values that appear non-intuitively lower than signal-combinations that might be expected to be “better.” However, this is actually due to limits in our observability.

Finally, recall that the performance standards provide assertions against which performance may be verified. The performance standards do not focus on the relative accuracy of any pair of signal combinations but establish the threshold to be achieved for each signal-combination.

C.3 Selection of Broadcast Navigation Message Data

Several of the processes used in deriving the results in this report are dependent on the broadcast navigation message data. In most cases, the clock, ephemeris, and integrity (CEI) data are required. These are contained in subframes 1, 2, and 3 of the GPS LNAV message and in Message Type (MT) 10, MT 11, and the front portion of MT 30-37 of the GPS CNAV messages. A CEI data set is broadcast by a given SV for a period in time. The CEI data sets nominally change every two hours for both LNAV and CNAV. The position and health status of the transmitting SV are derived from the CEI data.

The goal in selecting a CEI data set for a given SV at a given time of interest is to reproduce what the user would have experienced had they been collecting data from that SV at that time. To accomplish this, the process must have access to a complete time-history of navigation message data and it must properly select specific sets of CEI data from that time-history.

The CEI data sets supporting this analysis were collected from the NGA MSN, which has complete dual-station visibility to all GPS SVs (and generally, much better). The MSN data collection process captures the earliest transmission of each unique CEI data set. We investigated any gaps in the CEI data set time-history and filled such gaps, if practical. The result is a time-history of the unique CEI data sets transmitted by each SV.

Wherever the analysis process requires CEI data for a given SV at a given time, it selects the CEI data set that corresponds to what was being transmitted from the SV at that time. During periods in which new data is being transmitted (data set cutovers), the preceding CEI data set is used until the time the new CEI data set had been completely transmitted and available to the user.

It must be recognized that this may be an inexact reproduction of the experience of any given user. Users may experience delays in the receipt of newly transmitted navigation message data due to obstructions, atmospheric issues, or receiver problems. However, our process is deterministic and reproducible.

C.4 AOD Methodology

Near the end of October 2024, the navigation message correction table (NMCT) was deactivated. When this happened, the AOD offset (AODO) values changed behavior such that they are always at the maximum value, indicating no knowledge of the AOD. As a result, the process for calculating AOD was changed for November and December.

The new process is dependent on the block type of the SV.

- For GPS III SVs, the time of prediction (t_{op}) in the CNAV message is used as the beginning time for calculating AOD for all signals. Because the GPS III SVs receive state vector uploads, all the signals have the same AOD.
- For Block IIF, IIR, and IIR-M SVs, the process varies by signal.
 - For L2C and L5 signals, the CNAV t_{op} is used as the beginning time for the AOD calculation.
 - For the legacy signals, the AOD at cutover to a new upload is assumed to be 900 s. This is a rough statistical average based on past performance.

The process for AOD calculation from January through October 2024 is described as follows.

The AOD was calculated by finding the upload times based on the t_{oe} offsets as defined in IS-GPS-200 Section 20.3.4.5 and then examining the t_{nmct} under the following assumptions:

- A complete set of the subframe 1, 2, and 3 data broadcast by all SVs of interest is available throughout the time period of interest.
- The term t_{nmct} defined in IS-GPS-200 Section 20.3.3.4.4 represents the time of the Kalman state used to derive the corresponding navigation message.

Given these assumptions, the AOD at any point in time can be determined by the following process:

- Working backward from the time of interest to finding the time when the most recent preceding upload was first broadcast
- Finding the AODO of the associated subframe 2
- Subtracting the AODO from the t_{oe} (as described in IS-GPS-200 20.3.3.4.4) to determine the time of the Kalman state parameters
- Calculating the difference between the time of interest and the Kalman state parameter time

The search for the preceding upload is necessary because the AODO has a limited range and is not sufficient to maintain an accurate count for a complete upload cycle.

The results of this algorithm are generally consistent with the results provided by MCS analysis. The first assumption is fulfilled by the NGA MSN archive. The remaining assumption was discussed with systems engineers supporting 2 NWS and is believed to be valid.

The exception to this process is PRN 32. PRN 32 does not have the AODO term described due to limitations in the navigation message format. As a result, we cannot directly derive the AOD for PRN 32. For purposes of this report, we examined all upload cutovers through 2024 for all SVs except SVN 70/PRN 32. We computed the AOD at the time of each upload cutover. We then computed the mean of these samples to determine an average AOD at the time of the upload cutover. There were 11,329 samples with an average AOD of 931 s (about 15.5 minutes). We assumed this average holds true for SVN 70/PRN 32 and conducted the analysis accordingly.

Note that there is no need for a GPS receiver to calculate AOD. The URE as a function of AOD is one of the metrics evaluated for this report but is not a concern for a real-time user.

C.5 Position Methodology

Section 2.4.5 of SPS PS 2020 provides usage assumptions for the SPS PS 2020, and some of the notes in Section 2.4.5 are relevant to the question of position determination. The following is quoted from Section 2.4.5:

The performance standards in Section 3 of this SPS PS 2020 do not take into consideration any error source that is not under direct control of the Space Segment or Control Segment. Specifically excluded errors include those due to the effects of:

- *Signal distortions caused by ionospheric and/or tropospheric scintillation*
- *Residual receiver ionospheric delay compensation errors*
- *Residual receiver tropospheric delay compensation errors*
- *Receiver noise (including received signal power and interference power) and resolution*
- *Multipath and receiver multipath mitigation*
- *User antenna effects*
- *Operator (user) error*

In addition, at the beginning of Section 3.8, the SPS PS 2020 explains that in addition to the error exclusions listed in Section 2.4.5, the following assumptions are made regarding the SPS receiver:

The use of a representative SPS receiver that:

- *is designed in accordance with IS-GPS-200.*
- *is tracking the SPS SIS from all satellites in view above a 5° mask angle... It is assumed the receiver is operating in a nominal noise environment...*
- *accomplishes satellite position and geometric range computations in the most current realization of the 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.*
- *processes the health-related information in the SIS and excludes marginal and unhealthy SIS 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 a trackable SIS.*
- *is operating at a surveyed location (for a time transfer receiver).*

To address these assumptions, we adopted the following approach for computing a set of accuracy statistics:

1. 30 s GPS observations were collected from the NGA GPS monitor station network (MSN) and a similar set of IGS stations. This decision addressed the following concerns:
 - (a) All stations selected collect dual-frequency observations. Therefore, the first-order ionospheric effects can be eliminated from the results.
 - (b) All stations selected collect weather observations. The program that generates the positions uses the weather data to eliminate first-order tropospheric effects.
 - (c) The receiver thermal noise will not be eliminated, but both the NGA and IGS stations are equipped with the best available equipment, so effects will be limited.
 - (d) Similarly, multipath cannot be eliminated, but both networks use antennas designed for multipath reduction, and station sites were chosen to avoid the introduction of excessive multipath.
 - (e) Antenna phase center locations for such stations are precisely surveyed. Therefore, reference positions are readily available.
 - (f) Despite the similarities, the two networks are processed separately for a variety of reasons.
 - i. The NGA MSN uses receivers capable of tracking the Y-code. As a result, the individual observations have somewhat better SNR than the observations from the IGS stations.
 - ii. By contrast, the IGS stations are tracking L1 C/A and L2 codeless, then averaging their observations over 30 s in order to reduce noise on the data.
 - iii. The NGA MSN uses a single receiver type which limits the number of receiver-specific traits but leaves open the possibility that a systemic problem could affect all receivers. The IGS network uses a variety of receivers, which is some protection against systemic problems from a single receiver type, but requires that the processing address a variety of receiver-specific traits.
 - iv. The NGA MSN is operated and maintained by a single organization. Changes are planned and well-controlled. The IGS network is cooperative in nature. While policies are in place to encourage operational standards, changes in station behavior are not as well-coordinated.
2. Process the data using a comprehensive set of broadcast ephemerides collected as described in Appendix C.3.

3. Process the collected observations using the PRSOLVE program of the ARL:UT-hosted open source GNSS Toolkit (GNSSTk, formerly GPSTk)[19]. Note:
 - (a) PRSOLVE meets the relevant requirements listed above. For example, SV positions are derived in accordance with IS-GPS-200, the elevation mask is configurable, weather data is used to estimate tropospheric effects, and WGS 84 [12] conventions are used. Data from unhealthy SVs were removed from PRSOLVE using an option to exclude specific satellites.
 - (b) PRSOLVE is highly configurable. Several of the items in the preceding list of assumptions are configuration parameters to PRSOLVE.
 - (c) Any other organization that wishes to reproduce the results should be able to do so. (Both the algorithm and the data are publicly available.)
4. Process the collected 30 s observations in two ways:
 - (a) Use all SVs in view without data editing in an autonomous pseudorange solution to generate 30 s position residuals at all sites.
 - (b) Use a receiver autonomous integrity monitoring (RAIM) algorithm (another PRSOLVE option) to remove outlier pseudorange measurements from which a “clean” set of 30 s position residuals is generated at all sites. The RAIM algorithm used by PRSOLVE is dependent on several parameters. The two most important parameters are the RMS limit on the post-fit residuals (default: 3.0 m) and the number of SVs that can be eliminated in the RAIM process (default: unlimited). This analysis was conducted using the default values.
5. Compute statistics on each set of data independently.

C.6 Plane/Slot Methodology

As discussed in Section B.3, Appendix A.7.4 of the SPS PS 2020 defines a slot as being occupied when the footprint of a satellite (or combined footprint of a pair of satellites, for expanded slots) on the surface of the Earth overlaps at least 95% of the nominal slot's footprint, averaged over an orbit revolution. An approximation for this requirement is given in terms of offsets in Right Ascension of the Ascending Node (RAAN) and Argument of Latitude (ArgLat), computed as satellite value minus nominal slot value, as

$$\frac{1}{4}(\Delta\text{RAAN})^2 + (\Delta\text{ArgLat} + 0.5736 \times \Delta\text{RAAN})^2 \leq (0.0333 \text{ semi-circles})^2,$$

defining an ellipse within which a satellite occupies the slot. Appendix A.2.4 of the SPS PS 2020 defines how to propagate the nominal slot centers provided in Section 3.2 of the SPS PS 2020.

To determine plane/slot assignments, satellite position and velocity data are obtained from NGA PE at an hourly cadence, which are then converted to Keplerian orbital elements. At each epoch, the Keplerian orbital elements of the nominal slot locations are propagated forward in time. The plane each satellite resides in is determined using the computed RAAN values, and the slot occupancy condition is then checked for each slot in the occupied plane. The slot occupancy results are then averaged every 12 hours (roughly the orbital period of 11 hours and 56 minutes) to determine which slots, if any, a satellite occupied during its orbit. This yields two sets of slot assignments per day for each satellite, which are consolidated into a single slot assignment per satellite per day. Lastly, any potential instances of satellite pairs in “equivalent-or-better” non-standard configurations, as described in Appendix A.7.2.4 and Appendix A.7.2.5 of the SPS PS 2020, are checked, updating the slot assignment data as necessary. These plane-slot assignments are then used when computing metrics such as availability and continuity.

Appendix D

Acronyms and Abbreviations

Table D.1: List of Acronyms and Abbreviations

2 NWS	2 nd Navigation Warfare Squadron
2 SOPS	2 nd Space Operations Squadron
AMCS	Alternate Master Control Station
AOD	Age of Data
AODO	Age of Data Offset
ARL:UT	Applied Research Laboratories, The University of Texas at Austin
BC&P	Broadcast Clock and Position
CEI	Clock, Ephemeris, and Integrity
CMPS	Civil Monitoring Performance Specification
CNAV	Civil Navigation Message
DCB	Differential Code Bias
DECOM	Decommission (NANU Type)
DF	Dual Frequency
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DOP	Dilution of Precision
ECEF	Earth-Centered, Earth-Fixed
FAA	Federal Aviation Administration
FCSTDV	Forecast Delta-V (NANU Type)
FCSTEXTD	Forecast Extension (NANU Type)

FCSTMX	Forecast Maintenance (NANU Type)
FCSTRESCD	Forecast Rescheduled (NANU Type)
FCSTUUFN	Forecast Unusable Until Further Notice (NANU Type)
GDOP	Geometric Dilution of Precision
GEC	Groundtrack Equatorial Crossing
GLAN	Geographic Longitude of the Ascending Node
GNSS	Global Navigation Satellite System
GNSSTk	GNSS Toolkit
GPS	Global Positioning System
GPSTk	GPS Toolkit
HDOP	Horizontal Dilution Of Precision
ICD	Interface Control Document
IGS	International GNSS Service
IODC	Issue of Data, Clock
IODE	Issue of Data, Ephemeris
IS	Interface Specification
ISB	Inter-signal Bias
ISC	Inter-signal Correction
LNAV	Legacy Navigation Message
LSB	Least Significant Bit
MCS	Master Control Station
MSB	Most Significant Bit
MSN	Monitor Station Network
NANU	Notice Advisory to Navstar Users
NAV	Navigation Message
NAVSEA	U.S. Navy Naval Sea Systems Command
NGA	National Geospatial-Intelligence Agency
NMCT	Navigation Message Correction Table

NTE	Not to Exceed
OA	Operational Advisory
ORD	Observed Range Deviation
PCO	Antenna Phase Center Offset Corrections
PC&P	Precise Clock and Position
PDOP	Position Dilution of Precision
PE	Precise Ephemeris
PEO	Program Executive Office
PNT	Positioning, Navigation, and Timing
PPS	Precise Positioning Service
PPS PS 2007	2007 Precise Positioning Service Performance Standard
PRN	Pseudo-Random Noise
PVT	Position, Velocity, and Time
RAIM	Receiver Autonomous Integrity Monitoring
RINEX	Receiver Independent Exchange Format
RMS	Root Mean Square
RSS	Root Sum Square
SF	Single Frequency
SINEX	Station Independent Exchange Format
SIS	Signal-in-Space
SSC	Space Systems Command
SNR	Signal-to-Noise Ratio
SP3	Standard Product 3
SPS	Standard Positioning Service
SPS PS 2020	2020 Standard Positioning Service Performance Standard
SV	Space Vehicle
SVN	Space Vehicle Number
TDOP	Time Dilution of Precision

TF	Triple Frequency
T _{GD}	Group Delay Differential
UERAЕ	User-Equivalent Range Acceleration Error
UERE	User-Equivalent Range Error
UERRE	User-Equivalent Range Rate Error
UNUNOREF	Unusable with No Reference (NANU Type)
UNUSUFN	Unusable Until Further Notice (NANU Type)
URA	User Range Accuracy
URAE	User Range Acceleration Error
URE	User Range Error
URRE	User Range Rate Error
USCG	U.S. Coast Guard
USNO	U.S. Naval Observatory
USSF	U.S. Space Force
UTC	Coordinated Universal Time
UTCOE	UTC Offset Error
UUTCE	User UTC(USNO) Error
VDOP	Vertical Dilution of Precision
WGS 84	World Geodetic System 1984
ZAOD	Zero Age of Data

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