An Analysis of Global Positioning System Standard Positioning Service Performance for 2020

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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 2020 for the U.S. Space Force Space and Missile Systems Center Spectrum Warfare Division for PNT Mission Integration (ZACS-PNT). This report is based upon work supported by ZACS-PNT through Naval Sea Systems Command Contract N00024-17-D-6421, task order 5101030, "GNSS Signal Performance and Anomaly Analysis".

Performance is defined by the 2020 Standard Positioning Service (SPS) Performance Standard (SPS PS) [1]. The performance standard provides the U.S. government's assertions regarding the expected performance of GPS. This report does not address all of the assertions in the performance standards. 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 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. 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 the SPS PS assertions examined in this report were met in 2020.

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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 2020 for the U.S. Space Force Space and Missile Systems Center Spectrum Warfare Division for PNT Mission Integration (ZACS-PNT). This report is based upon work supported by ZACS-PNT through Naval Sea Systems Command Contract N00024-17-D-6421, task order 5101030, “GNSS Signal Performance and Anomaly Analysis”.

Performance is assessed relative to selected assertions in the 2020 Standard Positioning Service (SPS) Performance Standard (SPS PS) [1]. (Hereafter the term SPS PS, or SPSPS20, is used when referring to the 2020 SPS PS.) Chapter 2 contains a tabular summary of performance stated in terms of the metrics provided in the SPS PS. 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. 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 is conducted. Appendix D contains the acronyms and abbreviations.

The performance standards define services delivered through multiple signals. For the SPS PS, the signals and signal combinations are listed in Table 1.1. Four different GPS SV types were operational during 2020. Not all types are capable of broadcasting all signals. The signals broadcast by each type are shown in Table 1.2. 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 selection of signal-combinations directly examined in this report are described in Appendix C.1.

Table 1.1: SPS SIS Component Combinations Covered by SPSPS20

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

Table 1.2: SPS SIS Signals Present by Block in 2020

Block	SVNs	# SVs	L1 C/A	L2C	L5Q
IIR	41, 43, 44, 45, 46, 47, 51, 56, 59, 60, 61	11	✔	–	–
IIR-M	48, 50, 52, 53, 55, 57, 58	7	✔	✔	–
IIF	62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73	12	✔	✔	✔
III	74, 75, 76, 77	4	✔	✔	✔

The metrics 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, terrain masking, and foliage). This report addresses assertions in the SPS PS that can be verified by anyone with knowledge of standard GPS data analysis practices, familiarity with the relevant signal specification [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 assertions examined include those related to coverage, accuracy, continuity, availability, and position domain standards.

The majority of the assertions related to user range error (URE) values are evaluated by comparison of the space vehicle (SV) clock and position representations as computed from the broadcast GPS legacy navigation (LNAV) message and civil navigation message (CNAV) data against the SV truth clock and position data as provided by a precise orbit calculated after the time of interest. The URE process requires both broadcast clock and position data (BCP) and truth clock and position data (TCP). The process by which the URE values are calculated is described in Appendix C.2.

Observation data from tracking stations were used to cross-check the URE values and to evaluate non-URE assertions. Examples of the latter application include the areas of Continuity (Section 3.4), Availability (Section 3.5), and Position/Time Availability (Section 3.6). In these cases, data from two networks are 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. The geographic distribution of these stations is shown in Figure 1.1. The selection of these sets of stations ensure continuous simultaneous observation of all space vehicles by multiple stations. The assertions focus on SIS performance, which is not directly observable from ground tracking locations. To mitigate this problem, this performance review uses ionospherically-corrected dual-frequency observation data.

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.

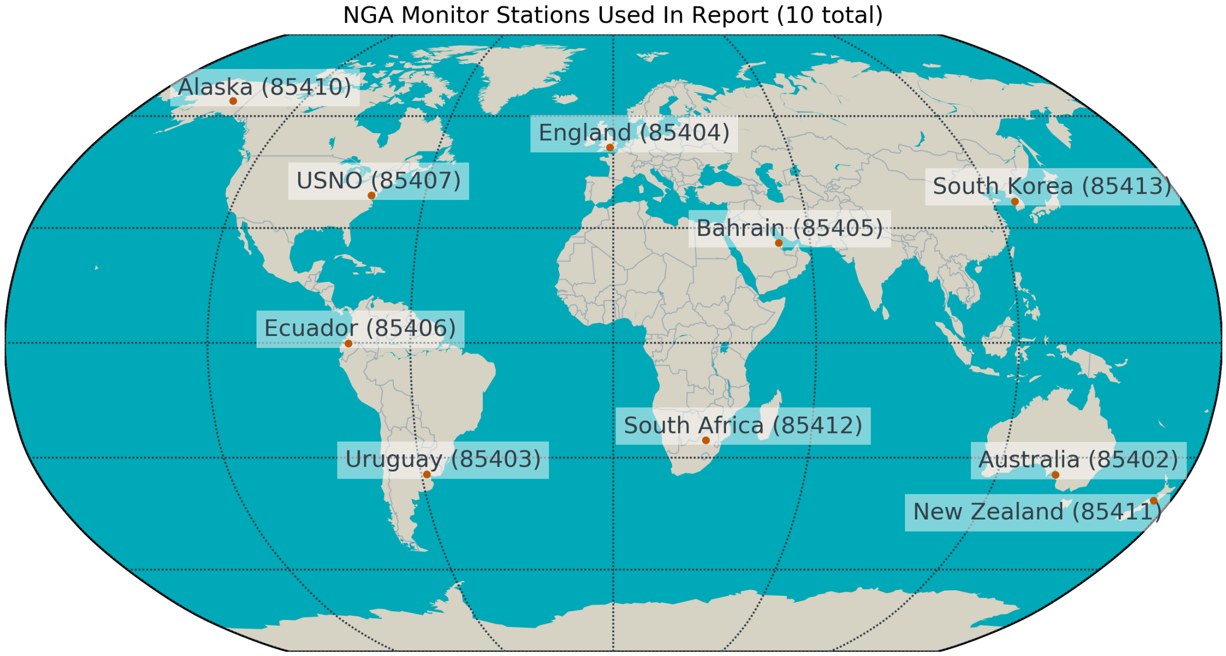
The majority of the metrics in this report are evaluated on either a per-SV basis or for the full constellation. The metrics associated with continuity and availability are defined with respect to the slot definitions. The slot definitions are stated in terms of either the Baseline 24 constellation, which consists of six orbital planes and 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, 27-28 were located in the Expandable 24 constellation in 2020. The SVs in excess of those located in defined slots are assigned to locations in various planes in accordance with operational considerations.

Each of the GPS SVs are identified by pseudo-random noise ID (PRN) and by space vehicle number (SVN). PRN IDs 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 the vehicle under discussion. As the number of active SVs has increased to the total available, 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] and the U.S. Naval Observatory (USNO) website [7]. See Appendix B.1 for a summary of the SVN-to-PRN mapping for 2020.

L5 was pre-operational during the period covered by this report and all L5 signals indicate an unhealthy status. As a result, deriving performance results for L5 requires a couple of assumptions. 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. 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.

The authors acknowledge and appreciate the effort of several ARL:UT staff members who reviewed these results. For 2020 this included Scott Sellers, David Munton, and Justin Yudichak.

Karl Kovach and Shannen Daly of The Aerospace Corporation provided valuable assistance in interpreting the SPSPS20 assertions. John Lavrakas of Advanced Research Corporation and P.J. Mendicki of The Aerospace Corporation have long been interested in GPS performance metrics and have provided valuable comments on the final draft. However, the results presented in this report are derived by ARL:UT, and any errors in this report are the responsibility of ARL:UT.



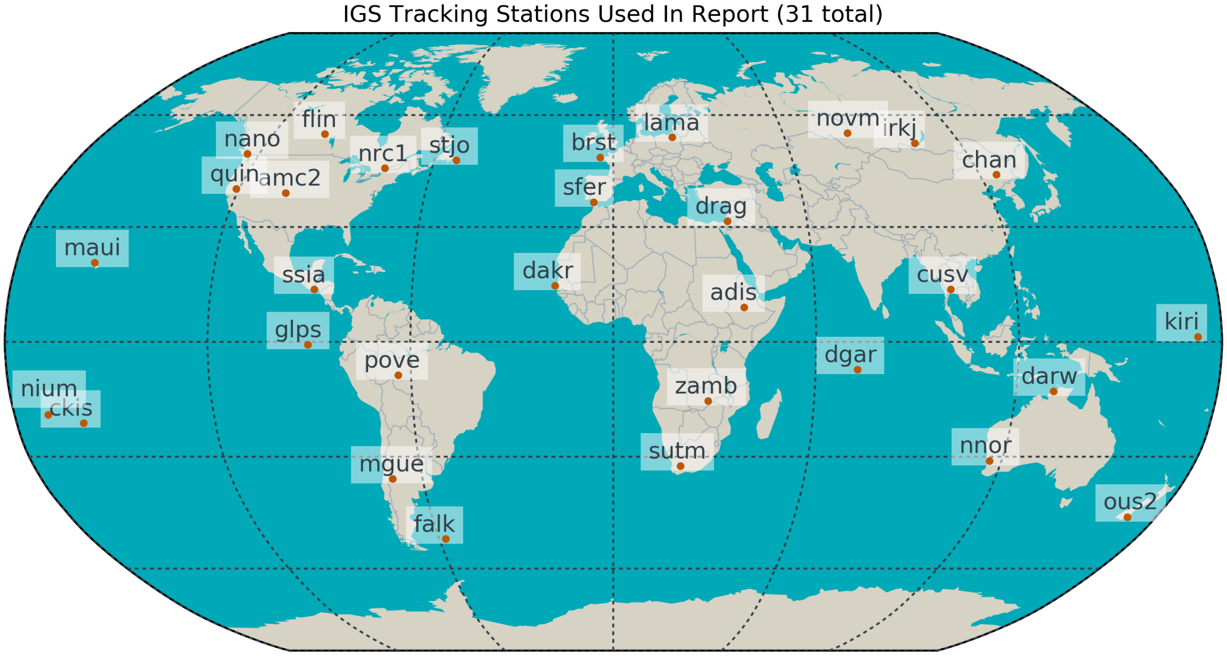


Figure 1.1: Maps of the Network of Stations Used in this Report

Chapter 2

Summary of SPS PS Results

Table 2.1 provides a summary of the assertions defined in SPSPS20. The table is annotated to show which assertions are evaluated in this report and the status of each assertion.

Of the assertions evaluated, all were met in 2020.

Details regarding each result may be found in Chapter 3. All abbreviations used in Table 2.1 may be found in Appendix D.

Table 2.1: Summary of SPS PS Metrics Examined for 2020

SPSPS20 Section	SPS PS 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	–	–	–	not eval.
3.3.2 SIS Constellation Coverage	100% Coverage of Terrestrial Service Volume	–	–	–	✔
3.4.1 SIS URE Accuracy	$\leq$ 7.0 m 95% Global Statistic URE during normal operations over all AODs	✔	✔	✔	–
	$\leq$ 9.7 m 95% Global Statistic URE during normal operations at any AOD	✔	✔	✔	–
	$\leq$ 3.8 m 95% Global Statistic URE during normal operations at zero AOD	✔	✔	✔	–
	$\leq$ 30 m 99.94% Global Statistic URE during normal operations	✔	✔	✔	–
	$\leq$ 30 m 99.79% Worst case single point Statistic URE during normal operations	✔	✔	✔	–
	$\leq$ 388 m 95% Global Statistic URE during extended operations after 14 days without upload	not eval.	–	–	–
	$\leq$ 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	$\leq$ 0.006 m/s 95% Global Statistic URRE during normal operations at any AOD	✔	✔	✔	–
3.4.3 SIS URAE Accuracy	$\leq$ 0.002 m/s^2 95% Global Statistic URAE during normal operations at any AOD	✔	✔	✔	–
3.4.4 SIS UTCOE Accuracy	$\leq$ 30 nsec 95% Global Statistic UTCOE during normal operations at any AOD	✔	✔	✔	–
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	✔	✔	✔	–
3.5.4 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	✔	✔	✔	–
3.5.5 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})	✔	✔	✔	–
	$\leq 1 \times 10^{-8}$ 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	$\geq$ 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	$\geq$ 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	$\geq$ 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	✔	–	–	–
	$\geq$ 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	$\geq$ 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	$\geq$ 98% Global PDOP of 6 or less	✔	–	–	–
	$\geq$ 88% Worst site PDOP of 6 or less	✔	–	–	–
3.8.2 Position Service Availability	$\geq$ 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	✔	–	–	–
3.8.3 Position/Velocity/Time Service Accuracy	$\leq$ 8 m 95% Horizontal error, global average	✔	–	–	–
	$\leq$ 13 m 95% Vertical error, global average	✔	–	–	–
	$\leq$ 15 m 95% Horizontal error, worst site	✔	–	–	–
	$\leq$ 33 m 95% Vertical error, worst site	✔	–	–	–
	$\leq$ 0.2 m/s 95% Velocity error, any axis	✔	–	–	–
	$\leq$ 30 nsec Time Transfer error 95% of the time	✔	–	–	–

✔ Assertion met ✗ Assertion not met
not eval. See report text for more information – No assertion

Table 2.2: References of SPS PS Metrics Examined for 2020

SPSPS20 Section	SPS PS 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	$\leq$ 7.0 m 95% Global Statistic URE during normal operations over all AODs	3.2.1
	$\leq$ 9.7 m 95% Global Statistic URE during normal operations at any AOD	3.2.2
	$\leq$ 3.8 m 95% Global Statistic URE during normal operations at zero AOD	3.2.3
	$\leq$ 30 m 99.94% Global Statistic URE during normal operations	3.2.4
	$\leq$ 30 m 99.79% Worst case single point Statistic URE during normal operations	
	$\leq$ 388 m 95% Global Statistic URE during extended operations after 14 days without upload	3.2.5
	$\leq$ 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	$\leq$ 0.006 m/s 95% Global Statistic URRE during normal operations at any AOD	3.2.6
3.4.3 SIS URAE Accuracy	$\leq$ 0.002 m/s^2 95% Global Statistic URAE during normal operations at any AOD	3.2.7
3.4.4 SIS UTCOE Accuracy	$\leq$ 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	$\geq$ 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	$\geq$ 0.957 Probability that (a.) a slot in the baseline 24-slot will be occupied by a satellite broadcasting a healthy 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	$\geq$ 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
	$\geq$ 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	$\geq$ 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	$\leq$ 8 m 95% Horizontal error, global average	3.6.3
	$\leq$ 13 m 95% Vertical error, global average	
	$\leq$ 15 m 95% Horizontal error, worst site	
	$\leq$ 33 m 95% Vertical error, worst site	
	$\leq$ 0.2 m/s 95% Velocity error, any axis	
	$\leq$ 30 nsec Time Transfer error 95% of the time	3.6.4

Chapter 3

Discussion of SPS PS Metrics and Results

While Chapter 2 summarizes the status of the SPSPS20 metrics for 2020, the statistics and trends reported in this chapter provide both additional information and support for those conclusions.

3.1 SIS Coverage

3.1.1 Per-Satellite Coverage

SIS per-satellite coverage is asserted in Section 3.3.1 of the SPSPS20. 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. This assertion is not evaluated at this time. Within the control segment, the operators have various tools to 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 SPSPS20. 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 2020. As a result, the assertion is considered verified for 2020.

3.2 SIS Accuracy

SIS URE accuracy is asserted in Section 3.4 of the SPSPS20. The following standards (from Tables 3.4-1 through 3.4-4 in the SPS PS) are considered in this report, for each SPS SIS Component Combination per SPSPS20 Table 2.2-2:

- *"$\leq$ 7.0 m 95% Global Statistic URE during Normal Operations over all AODs"*
- *"$\leq$ 9.7 m 95% Global Statistic URE during Normal Operations at Any AOD"*
- *"$\leq$ 3.8 m 95% Global Statistic URE during Normal Operations at Zero AOD"*
- *"$\leq$ 30 m 99.94% Global Statistic URE during Normal Operations"*
- *"$\leq$ 30 m 99.79% Worst Case Single Point Statistic URE during Normal Operations"*
- *"$\leq$ 388 m 95% Global Statistic URE during Extended Operations after 14 Days without Upload (C/A only)"*
- *"$\leq$ 2.0 m 95% Global Statistic URE during Normal Operations over all AODs for the ensemble of constellation slots"*
- *"$\leq$ 0.006 m/s 95% Global Statistic URRE over any 3-second interval during Normal Operations at Any AOD"*
- *"$\leq$ 0.002 m/s^2 95% Global Statistic URAE over any 3-second interval during Normal Operations at Any AOD"*
- *"$\leq$ 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 the Introduction). Throughout this report, an SV is considered healthy based on the definition in SPS PS Section 2.3.2.

The URE statistics presented in this report are based on a comparison of the BCP against the TCP (see also Appendix C).

3.2.1 URE Over All AOD

The performance standard URE metric that is most closely related to a user's observations is the calculation of the 95th percentile Global Statistic URE over all ages of data (AODs). This is associated with the SPSPS20 Section 3.4 metric:

- *"Each SPS SIS Component Combination per Table 2.2-2:*
  $\leq$ 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 are 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 SPSPS20 A.4.11 are applicable to computing statistics over both field-of-view and over time.
- *during Normal Operations* - This is a constraint related to normal vs. extended mode operations. See IS-GPS-200 20.3.4.4 [2] and Section A.4.
- *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 Section A.2.

In addition, the following general statements in Section 3.4 of SPSPS20 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."* (SPSPS20 Section 3.4, Note 2)

It is practical to compute a set of Instantaneous SIS URE values over a sufficiently dense spatial grid at fixed time intervals separated by uniform time steps throughout the period of interest. (See Appendix C.2.3 for details.) 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.) The 95th percentile values are then selected from the set of Instantaneous SIS URE values. We have computed the monthly statistic regardless of the number of days of availability in each month but have identified SV-months with fewer then 25 days of availability to note any SV-month with significantly less data than expected.

The results are organized by signal combination with parallel results for the various signal-combinations presented in the following tables and figures. 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. In all cases, no values exceed the stated threshold of 7.0 m, and so this requirement is met for 2020.

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 SPSPS20, even when only the worst performing month is considered. Even the worst value for each SV (indicated by the upper extent of the range bars) is more than factor of 2 smaller than 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 the 1.0 m level and whose range variation is small.
4. The values for SVN 65/PRN 24 and SVN 72/PRN 8 are noticeably different than the other Block IIF SVs. These are the only Block IIF SVs operating on a Cesium frequency standard.
5. Six SVs in Table 3.1 (and four in Tables 3.2 and 3.3) do not have values for an entire year, as three SVs were decommisioned and three SVs became initially usable (see Tables 3.10 and 3.11).

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	2020
41	14	IIR	0.83	0.67	0.77	1.11	0.93	0.92	0.81	–	–	–	–	–	0.89
43	13	IIR	1.00	0.94	1.17	1.40	0.94	0.87	0.82	0.94	0.98	0.76	0.90	0.82	0.97
44	28	IIR	2.01	2.40	2.27	1.99	2.09	2.22	2.00	2.16	2.47	2.10	1.99	1.96	2.15
45	21	IIR	1.18	1.08	1.09	1.12	1.45	1.21	1.32	1.18	1.30	1.27	1.34	1.55	1.28
46	11	IIR	1.02	1.07	0.83	0.75	0.92	0.90	0.77	0.70	0.87	1.03	0.96	–	0.90
47	22	IIR	1.21	1.22	1.22	1.35	1.35	1.15	1.27	1.18	1.11	1.09	1.18	1.30	1.23
48	7	IIR-M	0.83	0.92	0.85	1.04	0.84	0.91	0.89	1.00	0.96	0.98	1.02	0.94	0.94
50	5	IIR-M	0.82	1.06	0.91	0.66	0.77	0.85	0.71	0.73	0.87	0.78	0.70	0.87	0.83
51	20	IIR	1.10	1.07	0.97	1.27	1.09	0.93	1.11	1.10	1.21	1.29	1.04	1.15	1.14
52	31	IIR-M	0.92	1.06	0.92	0.89	1.14	0.94	1.01	0.99	0.97	1.07	1.03	1.03	1.00
53	17	IIR-M	1.46	1.58	1.47	1.65	1.34	1.34	1.54	1.40	1.50	1.72	1.25	1.53	1.47
55	15	IIR-M	0.78	0.64	0.46	0.43	0.74	0.55	0.51	0.65	0.70	0.74	0.66	0.51	0.65
56	16	IIR	0.81	0.89	0.79	0.84	0.64	0.70	0.76	0.70	0.81	0.82	0.78	0.93	0.81
57	29	IIR-M	1.14	1.01	1.19	0.84	1.08	1.17	1.21	0.92	1.00	1.13	0.95	0.91	1.06
58	12	IIR-M	0.55	0.50	0.53	0.49	0.75	1.41	0.64	0.56	0.63	0.50	0.51	0.67	0.62
59	19	IIR	1.28	1.24	1.17	1.18	1.35	1.19	1.09	1.16	1.15	1.07	1.25	1.42	1.23
60	23	IIR	0.78	0.65	0.53	–	–	–	–	–	–	–	–	–	0.71
61	2	IIR	1.02	0.96	1.01	1.11	1.07	0.99	1.00	1.01	0.92	1.02	1.02	1.20	1.03
62	25	IIF	0.71	0.94	0.89	1.05	0.90	0.79	0.77	0.80	0.88	1.06	0.95	0.79	0.91
63	1	IIF	1.03	0.82	1.07	0.86	0.81	1.50	1.17	0.80	0.82	0.93	1.19	1.06	1.02
64	30	IIF	0.70	0.73	0.83	0.76	0.85	1.05	1.11	0.91	0.54	0.77	0.95	0.68	0.92
65	24	IIF	2.67	2.63	2.49	2.51	2.19	2.37	2.70	2.37	2.43	2.67	2.40	2.47	2.52
66	27	IIF	0.56	0.60	0.58	0.61	0.57	0.52	0.64	0.60	0.63	0.55	0.57	0.58	0.59
67	6	IIF	1.50	1.51	1.37	1.33	1.23	1.38	1.15	1.27	1.19	1.16	1.19	1.23	1.33
68	9	IIF	1.23	0.80	0.99	0.76	0.60	0.55	0.66	0.82	0.69	0.59	0.98	0.47	0.80
69	3	IIF	1.50	1.12	1.13	1.17	0.96	0.98	0.89	1.05	1.01	1.00	1.12	1.32	1.15
70	32	IIF	0.81	0.95	1.02	0.80	0.69	0.65	0.75	0.71	0.96	0.81	0.87	0.85	0.84
71	26	IIF	1.05	0.69	0.64	0.57	0.56	0.62	0.63	0.55	0.55	0.59	0.69	0.68	0.67
72	8	IIF	2.00	2.44	2.08	2.16	2.25	2.16	2.31	2.13	2.44	1.95	2.00	2.40	2.22
73	10	IIF	0.74	0.69	0.88	0.78	0.63	0.75	0.92	0.99	0.78	0.91	0.83	0.95	0.83
74	4	III	0.89	0.99	1.07	1.03	0.97	0.85	0.92	0.98	0.95	0.73	0.85	0.78	0.94
75	18	III	–	–	–	1.97	1.80	1.11	1.06	0.88	0.78	0.71	0.93	0.90	1.62
76	23	III	–	–	–	–	–	–	–	–	–	0.93	0.85	0.68	0.85
77	14	III	–	–	–	–	–	–	–	–	–	–	–	2.72	2.72
Block IIR/IIR-M			1.11	1.13	1.08	1.16	1.17	1.12	1.15	1.10	1.15	1.14	1.13	1.27	1.14
Block IIF			1.46	1.46	1.34	1.32	1.24	1.33	1.41	1.26	1.33	1.25	1.27	1.37	1.34
GPS III			0.89	0.99	1.07	1.86	1.56	1.02	1.01	0.94	0.87	0.81	0.88	2.40	1.65
All SVs			1.23	1.25	1.19	1.40	1.21	1.18	1.20	1.14	1.19	1.15	1.15	1.57	1.23

Notes: Values not present indicate that the satellite was unavailable during this period. Months during which an SV was available 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 "2020" 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.

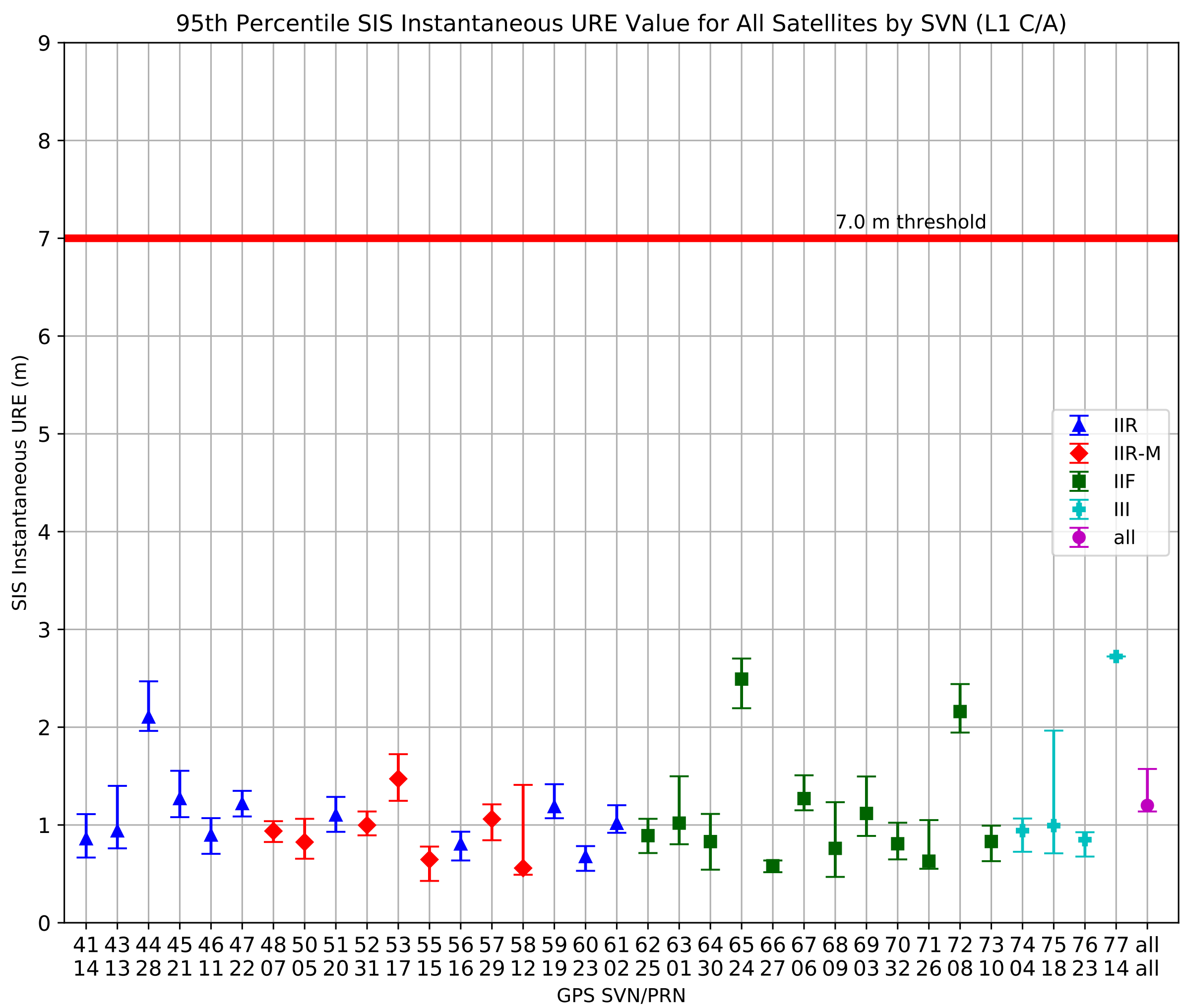


Figure 3.1: Range of the L1 C/A Monthly 95$^{\text{th}}$ Percentile Values for All SVs

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 along the vertical axis. The minimum and maximum of the monthly 95th percentile SIS URE for 2020 are shown by whiskers on the vertical bars. Color distinguishes 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 SPSPS20 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

SVN	PRN	Block	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2020
48	7	IIR-M	0.85	0.85	0.83	0.86	0.75	1.00	0.88	0.93	0.96	0.92	1.09	0.99	0.91
50	5	IIR-M	0.78	0.76	0.66	0.46	0.57	0.53	0.54	0.56	0.70	0.56	0.60	0.59	0.63
52	31	IIR-M	0.84	0.97	0.84	0.93	1.00	0.88	0.93	0.87	0.93	0.90	1.08	0.95	0.93
53	17	IIR-M	1.48	1.58	1.46	1.66	1.18	1.09	1.44	1.44	1.42	1.78	1.30	1.51	1.43
55	15	IIR-M	0.53	0.47	0.41	0.38	0.62	0.47	0.44	0.53	0.55	0.62	0.53	0.41	0.51
57	29	IIR-M	1.01	1.10	1.35	0.87	1.04	1.21	1.23	0.91	0.96	1.28	1.02	0.91	1.06
58	12	IIR-M	0.54	0.56	0.44	0.47	0.46	0.96	0.79	0.73	0.58	0.63	0.49	0.74	0.63
62	25	IIF	0.75	0.69	0.66	0.89	0.74	0.80	0.70	0.64	0.63	0.82	0.76	0.59	0.74
63	1	IIF	0.82	0.61	0.72	0.57	0.82	1.67	1.36	0.79	0.91	0.74	0.96	0.82	0.90
64	30	IIF	0.55	0.64	0.69	0.71	0.80	0.93	0.88	0.70	0.52	0.79	0.91	0.65	0.78
65	24	IIF	2.63	2.91	2.73	2.62	2.24	2.25	2.67	2.41	2.46	2.61	2.26	2.60	2.55
66	27	IIF	0.54	0.65	0.57	0.50	0.55	0.48	0.60	0.53	0.57	0.47	0.60	0.52	0.56
67	6	IIF	0.62	0.58	0.56	0.54	0.59	0.81	0.57	0.60	0.59	0.57	0.71	0.62	0.62
68	9	IIF	1.18	0.65	0.82	0.66	0.48	0.43	0.51	0.61	0.53	0.48	1.00	0.45	0.65
69	3	IIF	0.86	0.75	0.66	0.76	0.63	0.66	0.67	0.67	0.56	0.51	0.63	0.91	0.70
70	32	IIF	0.52	0.49	0.67	0.50	0.43	0.49	0.41	0.44	0.57	0.54	0.53	0.74	0.52
71	26	IIF	0.89	0.65	0.51	0.41	0.51	0.58	0.59	0.53	0.47	0.51	0.66	0.65	0.59
72	8	IIF	2.00	2.61	2.13	2.29	2.26	2.15	2.29	2.23	2.37	1.99	2.08	2.50	2.25
73	10	IIF	0.60	0.80	1.05	0.86	0.86	0.77	0.83	0.90	0.67	0.74	1.16	1.23	0.94
74	4	III	0.44	0.55	0.59	0.62	0.61	0.47	0.53	0.55	0.48	0.34	0.43	0.48	0.53
75	18	III	–	–	–	0.75	0.84	0.86	0.88	0.80	0.69	0.59	0.80	0.79	0.80
76	23	III	–	–	–	–	–	–	–	–	–	0.68	0.57	0.43	0.58
77	14	III	–	–	–	–	–	–	–	–	–	–	–	0.89	0.89
Block IIR-M			0.86	0.86	0.85	0.86	0.83	0.90	0.90	0.85	0.87	0.88	0.90	0.92	0.87
Block IIF			1.31	1.39	1.21	1.21	1.17	1.22	1.34	1.16	1.23	1.27	1.22	1.33	1.25
GPS III			0.44	0.55	0.59	0.69	0.76	0.76	0.81	0.74	0.64	0.58	0.67	0.73	0.70
All SVs			1.09	1.11	1.05	1.01	0.98	1.04	1.09	0.98	1.00	1.00	1.04	1.07	1.04

Notes: Values not present indicate that the satellite was unavailable during this period. Months during which an SV was available 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 "2020" 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.

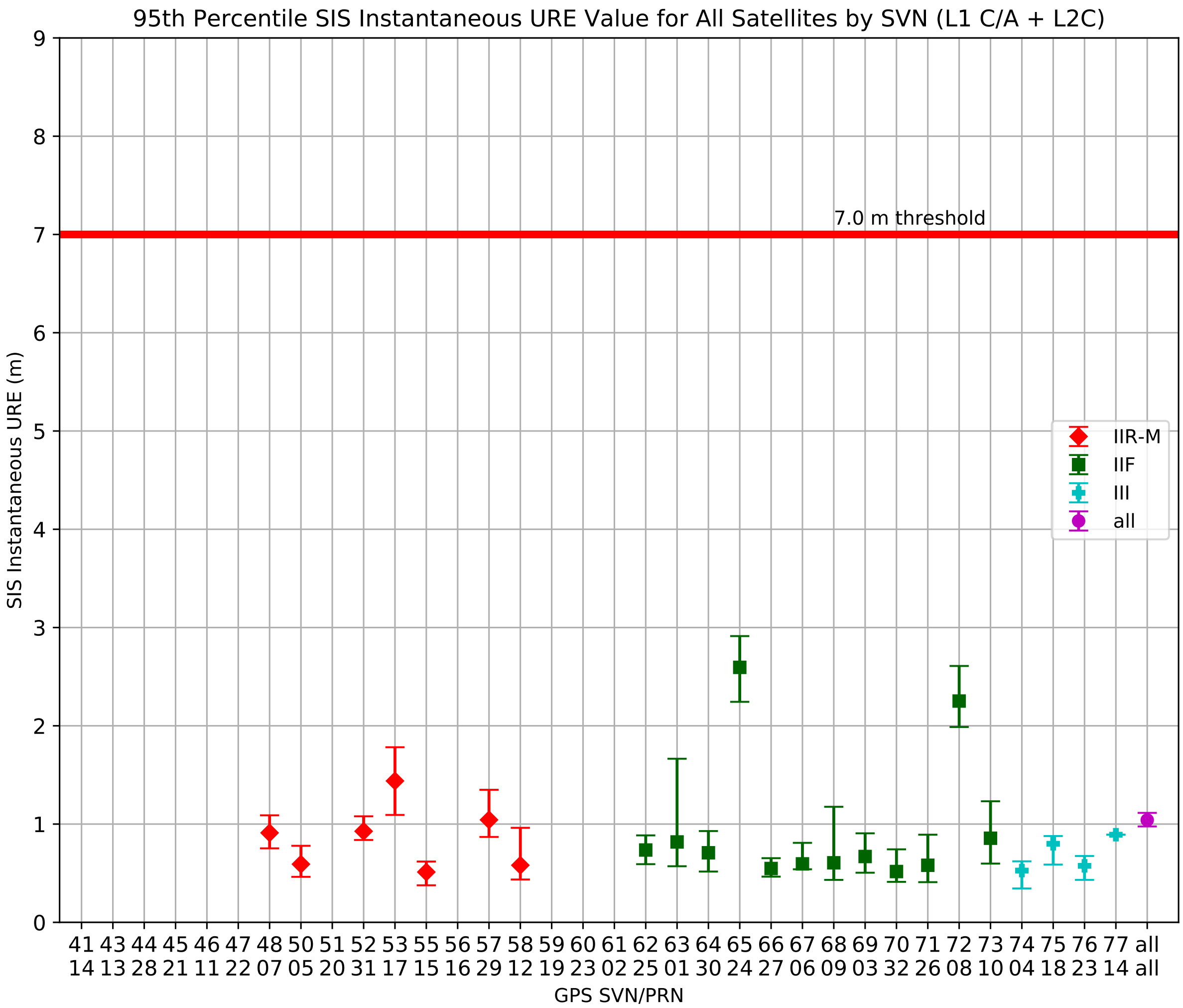


Figure 3.2: Range of the L1 C/A + L2C Monthly 95$^{\text{th}}$ Percentile Values for All SVs

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 along the vertical axis. The minimum and maximum of the monthly 95th percentile SIS URE for 2020 are shown by whiskers on the vertical bars. Color distinguishes 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 SPSPS20 Section 3.4 performance metric. The marker for "all" represents the monthly 95th percentile values across all satellites.

Table 3.3: Monthly 95$^{\text{th}}$ 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	2020
62	25	IIF	0.78	0.75	0.67	0.84	0.73	0.88	0.75	0.65	0.65	0.94	0.84	0.67	0.78
63	1	IIF	0.78	0.71	0.84	0.60	0.80	1.55	1.31	0.79	0.92	0.77	0.97	0.82	0.90
64	30	IIF	0.68	0.78	0.87	0.84	0.94	1.13	1.14	0.88	0.52	0.80	0.97	0.84	0.96
65	24	IIF	2.48	2.80	2.58	2.56	2.15	2.15	2.50	2.38	2.35	2.51	2.16	2.55	2.45
66	27	IIF	0.70	0.75	0.70	0.54	0.57	0.48	0.61	0.52	0.56	0.48	0.54	0.54	0.61
67	6	IIF	0.72	0.55	0.54	0.51	0.62	0.77	0.61	0.54	0.66	0.76	0.91	0.71	0.68
68	9	IIF	1.19	0.67	0.84	0.61	0.45	0.43	0.46	0.55	0.51	0.57	1.23	0.73	0.67
69	3	IIF	0.81	0.78	0.61	0.63	0.83	0.81	0.92	0.87	0.66	0.62	0.59	0.89	0.76
70	32	IIF	0.82	0.63	0.77	0.73	0.64	0.74	0.68	0.68	0.76	0.85	0.81	1.18	0.78
71	26	IIF	0.82	0.80	0.56	0.54	0.58	0.69	0.63	0.54	0.56	0.67	0.79	0.89	0.69
72	8	IIF	1.84	2.44	2.01	2.20	2.12	2.08	2.15	2.13	2.26	2.00	2.08	2.46	2.16
73	10	IIF	0.64	0.73	0.98	0.86	0.80	0.71	0.83	0.90	0.68	0.77	1.22	1.30	0.94
74	4	III	0.74	0.91	0.97	0.82	0.84	0.69	0.76	0.74	0.71	0.45	0.58	0.55	0.78
75	18	III	–	–	–	1.80	1.93	1.95	1.83	1.75	1.65	1.49	1.68	1.66	1.80
76	23	III	–	–	–	–	–	–	–	–	–	1.65	1.55	1.36	1.55
77	14	III	–	–	–	–	–	–	–	–	–	–	–	1.69	1.69
Block IIF			1.24	1.33	1.18	1.20	1.17	1.23	1.30	1.16	1.23	1.29	1.28	1.37	1.25
GPS III			0.74	0.91	0.97	1.71	1.83	1.84	1.74	1.67	1.58	1.52	1.57	1.53	1.66
All SVs			1.21	1.27	1.15	1.52	1.55	1.56	1.55	1.46	1.43	1.45	1.46	1.46	1.46

Notes: Values not present indicate that the satellite was unavailable during this period. Months during which an SV was available 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 "2020" 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.

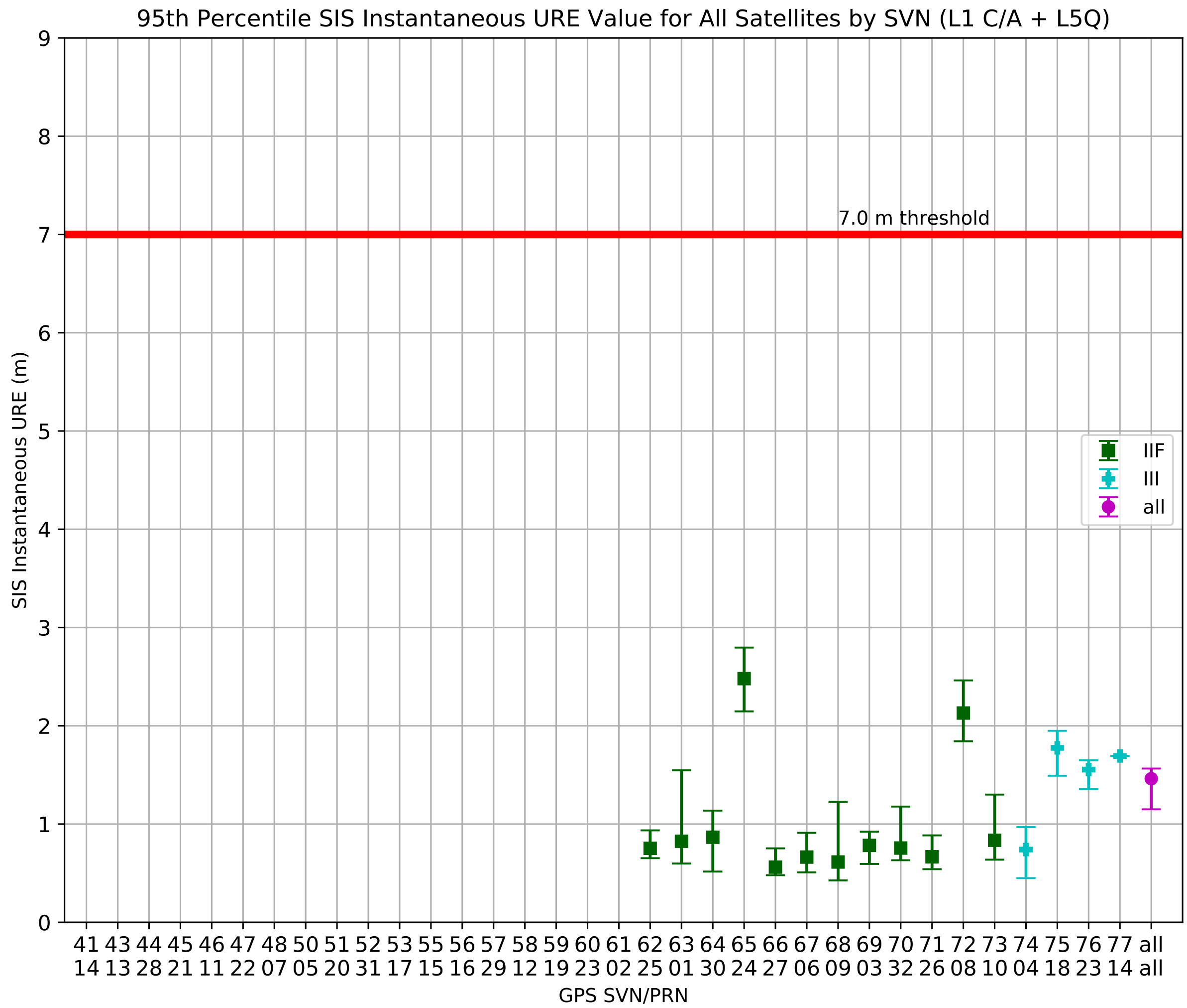


Figure 3.3: Range of the L1 C/A + L5Q Monthly 95th Percentile Values for All SVs

Notes: Each SVN with valid data is shown sequentially along the horizontal axis. The median value of the monthly 95th percentile SIS URE is displayed as a point along the vertical axis. The minimum and maximum of the monthly 95th percentile SIS URE for 2020 are shown by whiskers on the vertical bars. Color distinguishes 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 SPSPS20 Section 3.4 performance metric. The marker for "all" represents the monthly 95th percentile values across all satellites.

Using the L1 C/A monthly 95th percentile values as a basis for comparison, we compute the differences against (1.) the L1 C/A + L2C monthly 95th percentile values, and (2.) the L1 C/A + L5Q values. This allows us to examine the relative differences between the various signal combinations. Figure 3.4 plots these differences for each SV.

It should be noted that each of the combinations starts with the same broadcast orbit and the same precise orbit. The differences are due to the intersignal corrections (ISCs) and the differential code biases (DCBs) being used to evaluate the correctness of the ISCs, and the intersignal correction process. Appendix C.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 the following:

- The L1 C/A values are assumed as "truth" and the range of the differences against the monthly values for the other signal combinations are shown.
- The GPS III SVs are still relatively new, thus the DCB values may not have settled to a final estimate prior to the end of 2020.
- The ranges for SVN 75/PRN 18 appear out-of-family. However, looking at Table 3.1, the first two months of operation have higher monthly values than succeeding months. This could be either an issue of operational tuning or it may be that the DCB values used for truth comparison to T_{GD} could require time to settle. The single monthly value for SVN 77/PRN 14 is also higher than other SVs, but this may be an artifact of the same considerations and can be examined further in 2021.

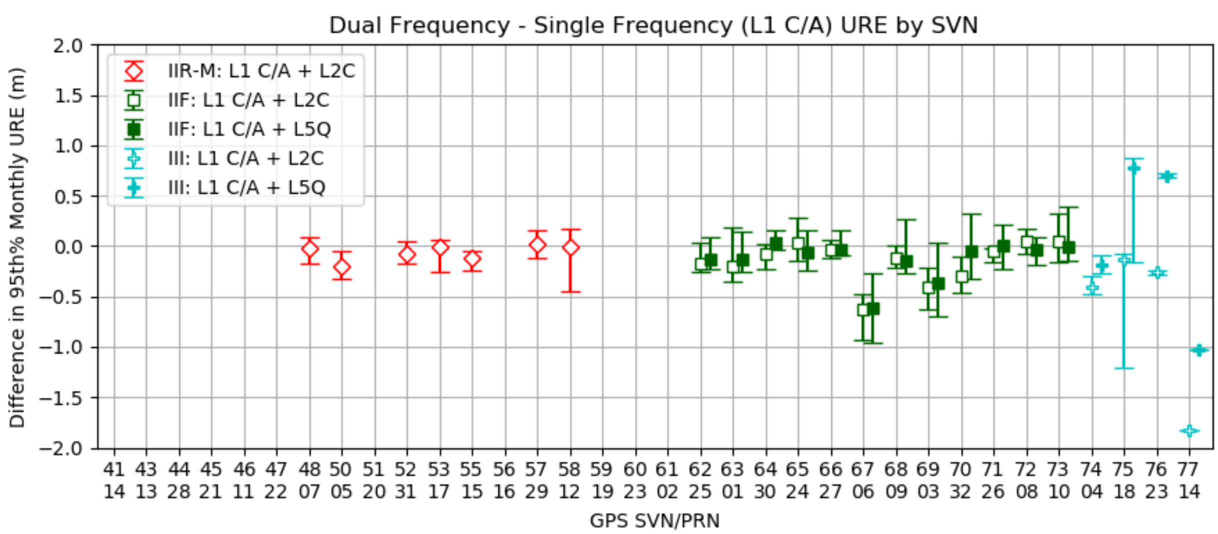


Figure 3.4: Range of Differences in Monthly Values between Dual-Frequency and L1 C/A UREs for All SVs

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 along the vertical axis. The minimum and maximum of the difference for 2020 are shown by whiskers on the vertical bars. Color distinguishes between the Block IIR-M, Block IIF, and GPS III SVs.

3.2.1.1 Constellation URE

The constellation accuracy is asserted in Section 3.4.1 of the SPSPS20. The assertion is contained in the last row of SPSPS20 Table 3.4-1.

- *"$\leq$ 2.0 m 95% Global Statistic URE during normal operations over all AODs for the ensemble of constellation slots"*

This is asserted to be true for all signal combinations in SPSPS20 Table 2.2-2.

This assertion is different from the preceding SIS URE assertions in that this assertion is across all the SVs occupying slots rather than by-SV. A similar process is used to derive a monthly statistic; however, the values for all trackable, healthy SV-epochs are included in the statistic rather than considering one SV at a time.

Figures 3.1, 3.2, and 3.3 show the constellation results as the rightmost range of values labled "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. As seen, these values are all below 2.0 m, thus the assertion is met.

This is a slightly larger population than the set of SVs that occupy slots. As shown in Appendix B, of the 31 operational SVs, there were usually 28 SVs in slots. However, the constellation values shown have sufficient margin that the assertion is met.

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	2020
L1 C/A	1.23	1.25	1.19	1.40	1.21	1.18	1.20	1.14	1.19	1.15	1.15	1.57	1.23
L1 C/A + L2C	1.09	1.11	1.05	1.01	0.98	1.04	1.09	0.98	1.00	1.00	1.04	1.07	1.04
L1 C/A + L5Q	1.21	1.27	1.15	1.52	1.55	1.56	1.55	1.46	1.43	1.45	1.46	1.46	1.46

Notes: Values not present indicate that the signal was unavailable during this period. Months during which a signal was available 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 "2020" 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 SPSPS20 Section 3.4 metric:

- *"$\leq$ 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 $\leq$ 9.7 m. See Section A.2 for a discussion of how the AOD is computed.

To examine this requirement, the set of 30 s Instantaneous RMS SIS URE values used in Section 3.2.1 was analyzed as described in Appendix A.5. In summary, the RMS SIS 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:

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

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.

For satellites that are operating on the normal pattern (roughly one upload per day), the count of points in each bin is roughly equal from the time the upload becomes available until about 24 hours AOD. In fact, 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 bin. This corresponds well to the plateau area of the green curve for the well-performing satellites. For satellites that are uploaded more frequently, the green curve will show a left-hand peak higher than the nominal count decreasing to the right. This is a result of the fact that there will be 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 constant value to aid in comparisons between the charts.

The representative best performers for Block IIR, Block IIR-M, and Block IIF are shown in Figures 3.5, 3.7, and 3.9. These are SVN 56/PRN 16, SVN 55/PRN 15, and SVN 66/PRN 27, respectively. For all blocks, several SVs have similar good results. Best performers exhibit a low and very flat distribution of AODs, and the UREs appear to degrade roughly linearly 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, and 3.10 show the worst performing (i.e. highest URE values) Block IIR, Block IIR-M, and Block IIF SVs. These are SVN 44/PRN 28, SVN 53/PRN 17, and SVN 65/PRN 24, respectively. Note that the distribution of AOD samples for SVN 65/PRN 24 is biased toward shorter values of AOD, which indicates that uploads are occurring more frequently than once-per-day on occasion.

Best and worst performers for the GPS III SVs were not selected as only one of the SVs was operational for all twelve months and two became operational in the last three months of the year.

The plots for all satellites are contained in Appendix A.5. A review of the full set of plots leads to the conclusion that the rate of URE growth for the two Block IIF SVs using Cesium frequency standards is noticeably higher. 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 SPSPS20 Section 3.4 metric:

- *"$\leq$ 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 blue lines shown in Figure 3.5 through Figure 3.10. 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.

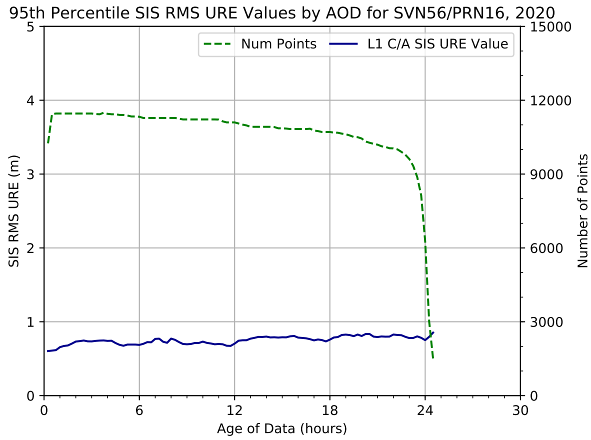


Figure 3.5: Best Performing Block IIR SV in Terms of URE over Any AOD

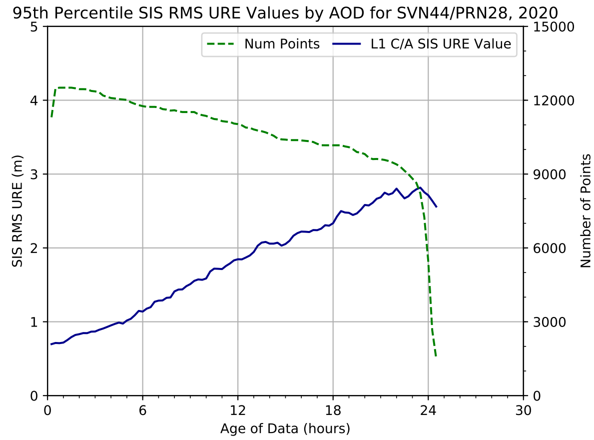


Figure 3.6: Worst Performing Block IIR SV in Terms of URE over Any AOD

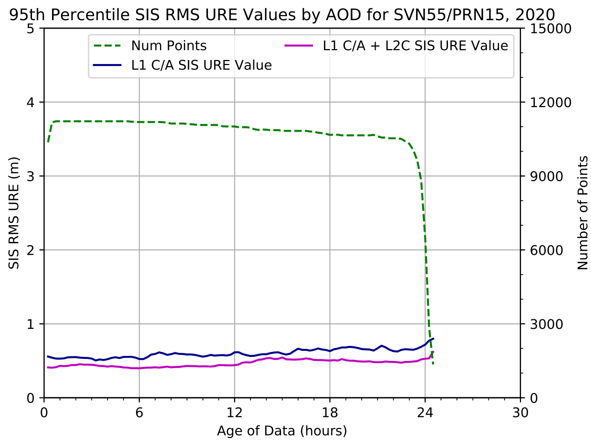


Figure 3.7: Best Performing Block IIR-M SV in Terms of URE over Any AOD

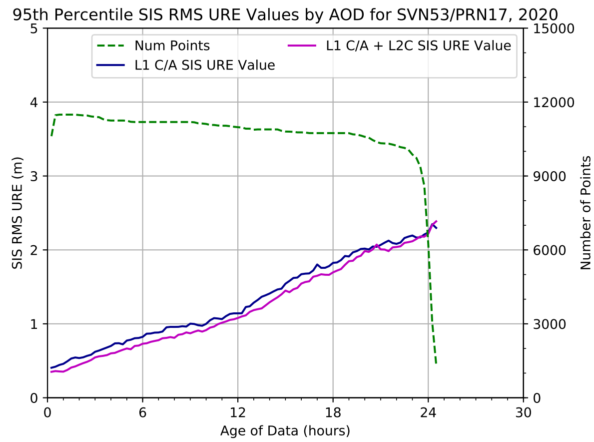


Figure 3.8: Worst Performing Block IIR-M SV in Terms of URE over Any AOD

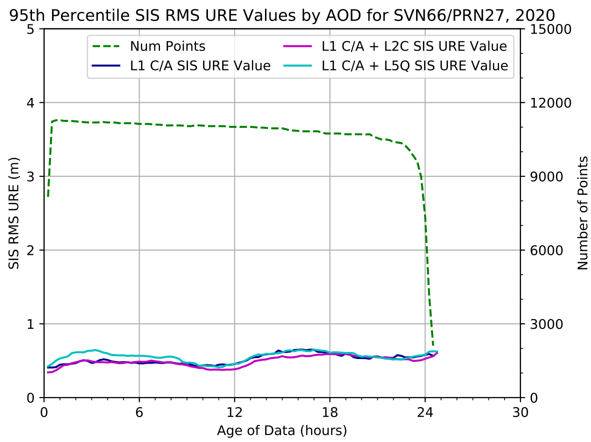


Figure 3.9: Best Performing Block IIF SV in Terms of URE over Any AOD

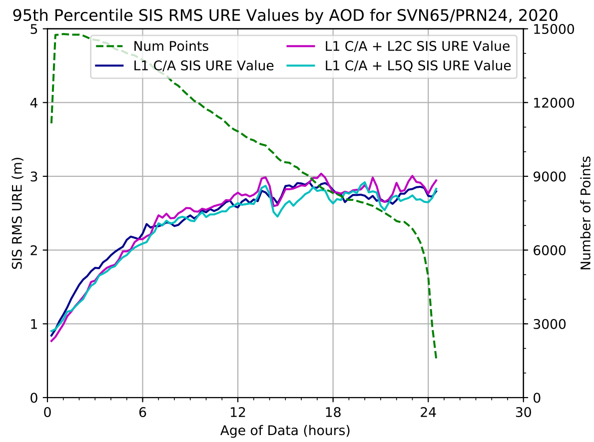


Figure 3.10: Worst Performing Block IIF SV in Terms of URE over Any AOD

3.2.4 URE Bounding

The SPSPS20 asserts the following requirements:

- *"$\leq$ 30 m 99.94% Global Statistic URE during Normal Operations"*
- *"$\leq$ 30 m 99.79% Worst Case Single Point Statistic URE during Normal Operations"*

The conditions and constraints are not entirely clear regarding the averaging periods for these statistics. Therefore, the Instantaneous SIS URE values computed as part of the evaluation described in Appendix C.2.3 were checked to determine whether any exceeded the 30 m threshold. This provides a set of 577 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 atmospheric effects 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.

Neither of these checks found any values that exceeded the 30 m threshold. Based on these results, these assertions are considered satisfied.

3.2.5 URE After 14 Days Without Upload

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

- *"$\leq$ 388 m 95% Global Statistic URE during Extended Operations after 14 Days without Upload"*

This standard is not evaluated as there were no periods in 2020 during which SVs were transmitting a healthy signal while operating after 14 days without an upload. See Appendix A.4.1 for information on the unhealthy extended operations test on SVN 76/PRN 23.

3.2.6 URRE Over All AOD

The SPS PS provides the following assertion for the user range rate error (URRE). This is subject to the same general constraints from SPSPS20 Section 3.4 as the URE assertions.

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

The URRE cannot be evaluated by comparison of the BCP to the TCP. This is due to two factors:

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

In the precise orbits used for the TCP, the noise due to the SV clocks is smoothed over long periods. As a result, the comparison of BCP and TCP 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 TCP along with the measured carrier phase observations and the known station positions to form the URRE values by differencing the range errors [8]. 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.

The observation data from the NGA MSN is collected at a 1.5 s rate. This rate allows examination of the URRE at the desired cadence. Dual-frequency observations (L1 P(Y) + L2 P(Y)) are used in order to reduce ionospheric errors and come as close as practical to the constraint that the results are to be based on SIS. In a similar manner, a tropospheric model based on weather observed at the stations is used to reduce tropospheric errors.

The preceding steps create a 1.5 s time-series of URRE values for each SV-receiver combination. The set of time-series for each SV are averaged across receivers at each epoch in order to form a time-series of URRE for each SV. These results are grouped for each month for a given SV for all healthy, trackable periods. Since results are signed values, the 2.5% and 97.5% values are selected as the bounds of the 95^{th}%. These values are typically near-identical except for the sign. Therefore, the larger of the two is used as the 95^{th}% value. These are the results shown in Table 3.5 and Figure 3.11.

While the results are labeled as "URRE" in Table 3.5 and Figure 3.11, it should be noted that these actually user-equivalent range rate errors (UERRE) as defined in Note 2 to SPS PS 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 room temperature, and the effect of the frequency standard that is associated with the receiver.

This means that the results may be regarded as an over bound on the actual URRE. If the results are within the assertion then the actual URRE must also be within the assertion as the URRE has to be smaller than the UERRE.

No values in Table 3.5 exceed 0.006 m/sec (6 mm/sec) and so this requirement is considered met for 2020.

Table 3.5: Monthly 95th Percentile Values of L1 P(Y) + L2P(Y) SIS RMS URRE for All SVs in mm/s

SVN	PRN	Block	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
41	14	IIR	2.59	2.59	2.63	2.61	2.65	2.63	2.64	–	–	–	–	–
43	13	IIR	2.77	3.27	3.26	3.15	3.04	2.74	2.77	3.29	3.24	3.47	3.43	2.76
44	28	IIR	2.71	2.68	2.71	2.69	2.77	2.77	2.80	2.79	2.77	2.73	2.86	2.78
45	21	IIR	3.10	2.96	2.93	3.02	3.25	3.29	3.07	2.94	2.96	3.09	3.41	3.31
46	11	IIR	2.84	2.80	2.82	2.88	2.88	2.87	2.90	2.90	2.90	2.89	2.90	–
47	22	IIR	2.74	2.73	2.60	2.50	2.57	2.67	2.79	2.74	2.68	2.59	2.81	2.82
48	7	IIR-M	2.71	2.62	2.70	2.81	2.93	2.79	2.72	2.71	2.79	2.88	3.06	2.88
50	5	IIR-M	3.88	3.85	3.53	3.22	3.30	3.60	3.83	3.78	3.54	3.30	3.53	3.69
51	20	IIR	2.71	2.71	2.68	2.63	2.71	2.71	2.75	2.75	2.69	2.69	2.83	2.77
52	31	IIR-M	2.54	2.49	2.52	2.57	2.66	2.58	2.55	2.55	2.60	2.65	2.81	2.62
53	17	IIR-M	3.02	3.03	3.21	3.13	3.04	2.98	2.99	3.09	3.23	3.11	3.13	3.08
55	15	IIR-M	2.69	2.79	2.82	2.70	2.65	2.60	2.68	2.78	2.87	2.74	2.78	2.65
56	16	IIR	3.36	3.13	3.02	2.96	3.07	3.20	3.23	3.08	2.98	2.98	3.22	3.36
57	29	IIR-M	2.70	2.70	2.79	2.75	2.75	2.72	2.74	2.78	2.85	2.77	2.85	2.75
58	12	IIR-M	3.25	3.02	2.94	2.91	2.99	3.13	3.16	2.99	2.93	2.93	3.10	3.24
59	19	IIR	2.72	2.70	2.73	2.69	2.71	2.70	2.72	2.75	2.80	2.77	2.89	2.82
60	23	IIR	2.52	2.50	2.50	–	–	–	–	–	–	–	–	–
61	2	IIR	2.48	2.48	2.48	2.48	2.56	2.52	2.51	2.53	2.53	2.52	2.61	2.54
62	25	IIF	1.82	1.81	1.82	1.81	1.86	1.85	1.84	1.88	1.89	1.85	1.97	1.86
63	1	IIF	2.05	2.02	2.02	1.99	2.05	2.04	2.02	2.05	2.07	2.03	2.19	2.04
64	30	IIF	1.79	1.79	1.78	1.78	1.86	1.85	1.84	1.88	1.88	1.85	2.00	1.86
65	24	IIF	5.69	5.69	5.68	5.67	5.70	5.70	5.67	5.68	5.72	5.71	5.76	5.72
66	27	IIF	1.97	1.96	1.95	1.94	2.00	1.99	2.00	2.04	2.04	2.00	2.12	2.00
67	6	IIF	1.87	1.84	1.84	1.81	1.88	1.88	1.86	1.88	1.90	1.88	2.04	1.88
68	9	IIF	1.77	1.76	1.74	1.74	1.80	1.80	1.80	1.81	1.82	1.79	1.96	1.84
69	3	IIF	1.74	1.72	1.71	1.71	1.77	1.77	1.78	1.79	1.81	1.78	1.98	1.86
70	32	IIF	1.79	1.80	1.79	1.79	1.87	1.83	1.83	1.87	1.86	1.84	1.94	1.84
71	26	IIF	1.93	1.91	1.90	1.87	1.94	1.92	1.97	2.05	2.07	1.95	2.05	1.91
72	8	IIF	4.20	4.22	4.23	4.23	4.26	4.31	4.33	4.37	4.41	4.39	4.46	4.45
73	10	IIF	1.83	1.81	1.79	1.79	1.88	1.86	1.89	1.91	1.92	1.91	2.04	1.90
74	4	III	1.76	1.76	1.74	1.74	1.84	1.81	1.81	1.84	1.82	1.81	2.03	1.85
75	18	III	–	–	–	1.78	1.87	1.84	1.84	1.86	1.84	1.85	2.02	1.84
76	23	III	–	–	–	–	–	–	–	–	–	1.85	2.00	1.87
77	14	III	–	–	–	–	–	–	–	–	–	–	–	1.90
All SVs			5.69	5.69	5.68	5.67	5.70	5.70	5.67	5.68	5.72	5.71	5.76	5.72

Notes: Values not present indicate that the satellite was unavailable during this period. Months during which an SV was available for less than 25 days are shown shaded. Months with the highest URRE for a given SV are colored red. The row at the bottom is the monthly 95th percentile values over all SVs.

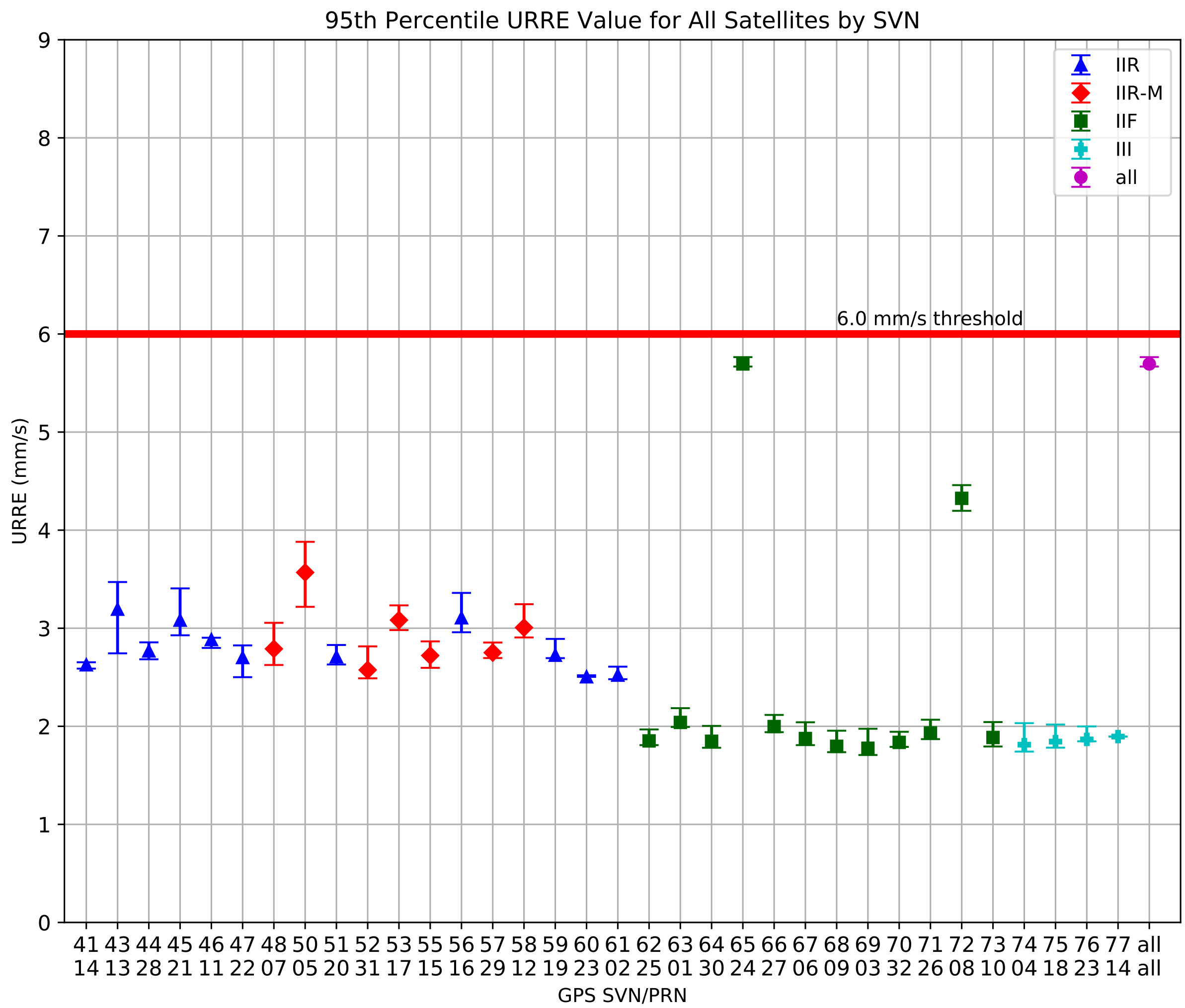


Figure 3.11: Range of the Monthly URRE 95$^{\text{th}}$ Percentile Values for All SVs

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 along the vertical axis. The minimum and maximum of the monthly 95th percentile URRE for 2020 are shown by whiskers on the vertical bars. Color distinguishes between the Block IIR, Block IIR-M, Block IIF, and GPS III SVs. The red horizontal line at 6.0 mm/s indicates the upper bound given by the SPSPS20 Section 3.4 performance metric. The marker for "all" represents the monthly 95th percentile values across all satellites.

3.2.7 URAE Over All AOD

The SPS PS 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 SPSPS20 Section 3.4 as the URE assertions.

The URAE values were obtained by differencing the URRE values derived in support of the previous section [8]. 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 3.12 provides a summary of these results for the entire constellation.

The values in Table 3.6 are all below the assertion threshold of 2 mm/sec/sec, except for the values associated with SVN 65/PRN 24. Those values are consistently above the threshold, but by less than 5%. Recall that these are actually user-equivalent range acceleration errors (UERAE) and include receiver effects as discussed in Section 3.2.6 regarding the URRE.

Of the various data sets included in this analysis, the data collected by the NGA monitor station at USNO have slightly lower noise characteristics due to the fact that the station derives its time from the USNO master clock. When the data from the station at USNO are process in isolation, the UERAE results are 6 - 7% lower and therefore fall within the assertion. This is illustrated by the extra row for SVN 65/PRN 24 in Table 3.6 which shows the values when only USNO data is considered. In Figure 3.12 two sets of values are shown for SVN 65/PRN 24 with the values derived with only the USNO data labeled as such. This provides confidence that the URAE is below the threshold while the results averaged across all the stations provide confidence that there are no large outliers in cases in which data are out of view of the station at USNO.

The "All SV" row in Table 3.6 and the "all" values in Figure 3.12 also contain values above the 2 mm/sec/sec threshold. These results are dominated by the SVN 65/PRN 24 values. There is no assertion "over all SVs" in the SPS PS so the fact these values are above the threshold is not relevant to meeting the assertion if the individual SVs values are acceptable.

Given the preceding explanation, this requirement is considered met for 2020.

Table 3.6: Monthly 95th Percentile Values of L1 P(Y) + L2P(Y) SIS RMS URAE for All SVs in mm/s^2

SVN	PRN	Block	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
41	14	IIR	0.93	0.94	0.94	0.94	0.97	0.95	0.95	–	–	–	–	–
43	13	IIR	1.02	1.08	1.10	1.07	1.08	1.06	1.05	1.11	1.10	1.12	1.17	1.06
44	28	IIR	0.97	0.97	0.98	0.97	1.01	1.00	1.00	1.01	0.99	0.99	1.06	1.01
45	21	IIR	0.94	0.93	0.93	0.95	1.00	0.98	0.94	0.93	0.93	0.96	1.05	1.02
46	11	IIR	1.03	1.02	1.02	1.02	1.04	1.04	1.05	1.06	1.06	1.06	1.06	–
47	22	IIR	0.86	0.86	0.85	0.84	0.86	0.87	0.89	0.89	0.87	0.87	0.97	0.94
48	7	IIR-M	0.94	0.92	0.92	0.94	0.98	0.96	0.94	0.95	0.96	0.97	1.04	0.99
50	5	IIR-M	1.10	1.08	1.04	1.00	1.03	1.06	1.09	1.08	1.05	1.02	1.11	1.08
51	20	IIR	0.93	0.93	0.92	0.92	0.96	0.94	0.95	0.95	0.94	0.94	1.01	0.96
52	31	IIR-M	0.91	0.90	0.89	0.89	0.92	0.91	0.90	0.91	0.91	0.92	1.00	0.92
53	17	IIR-M	0.94	0.94	0.97	0.95	0.96	0.94	0.94	0.96	0.98	0.96	1.01	0.98
55	15	IIR-M	0.94	0.95	0.95	0.93	0.94	0.93	0.93	0.95	0.97	0.95	1.01	0.95
56	16	IIR	1.02	0.99	0.98	0.97	1.01	1.02	1.02	1.02	0.99	0.99	1.08	1.04
57	29	IIR-M	0.87	0.88	0.88	0.88	0.91	0.90	0.89	0.91	0.91	0.90	0.96	0.90
58	12	IIR-M	0.93	0.90	0.89	0.89	0.91	0.93	0.92	0.91	0.90	0.90	0.97	0.94
59	19	IIR	0.95	0.94	0.93	0.91	0.94	0.93	0.93	0.94	0.95	0.96	1.02	0.99
60	23	IIR	0.91	0.90	0.89	–	–	–	–	–	–	–	–	–
61	2	IIR	0.87	0.87	0.88	0.88	0.92	0.89	0.89	0.89	0.89	0.89	0.94	0.91
62	25	IIF	0.83	0.83	0.83	0.83	0.84	0.84	0.83	0.85	0.86	0.84	0.89	0.85
63	1	IIF	0.95	0.94	0.93	0.92	0.94	0.93	0.92	0.93	0.94	0.93	1.00	0.94
64	30	IIF	0.82	0.82	0.81	0.81	0.84	0.83	0.83	0.84	0.85	0.83	0.91	0.85
65	24	IIF	2.06	2.05	2.04	2.04	2.05	2.05	2.04	2.05	2.06	2.05	2.08	2.05
65*	24*	IIF	1.92	1.92	1.91	1.93	1.96	1.95	1.91	1.92	1.93	1.93	1.94	1.92
66	27	IIF	0.91	0.90	0.90	0.89	0.92	0.91	0.92	0.93	0.93	0.92	0.97	0.93
67	6	IIF	0.87	0.85	0.85	0.83	0.86	0.85	0.84	0.85	0.87	0.86	0.94	0.87
68	9	IIF	0.82	0.82	0.81	0.80	0.83	0.83	0.82	0.83	0.84	0.82	0.91	0.86
69	3	IIF	0.80	0.79	0.78	0.78	0.81	0.81	0.81	0.81	0.82	0.81	0.91	0.87
70	32	IIF	0.83	0.83	0.82	0.82	0.86	0.84	0.83	0.85	0.85	0.84	0.89	0.85
71	26	IIF	0.89	0.88	0.88	0.86	0.89	0.88	0.90	0.93	0.95	0.89	0.94	0.88
72	8	IIF	1.57	1.57	1.57	1.55	1.57	1.59	1.60	1.61	1.63	1.62	1.65	1.63
73	10	IIF	0.84	0.83	0.82	0.82	0.86	0.85	0.86	0.87	0.87	0.87	0.93	0.87
74	4	III	0.80	0.80	0.80	0.79	0.83	0.82	0.82	0.83	0.82	0.82	0.93	0.85
75	18	III	–	–	–	0.81	0.85	0.83	0.83	0.84	0.83	0.84	0.91	0.84
76	23	III	–	–	–	–	–	–	–	–	–	0.84	0.91	0.86
77	14	III	–	–	–	–	–	–	–	–	–	–	–	0.87
All SVs			2.06	2.05	2.04	2.04	2.05	2.05	2.04	2.05	2.06	2.05	2.08	2.05

*Notes: Values not present indicate that the satellite was unavailable during this period. Months during which an SV was available for less than 25 days are shown shaded. Months with the highest 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 65/PRN 24 indicates use of USNO data only. See Section 3.2.7 for more information.*

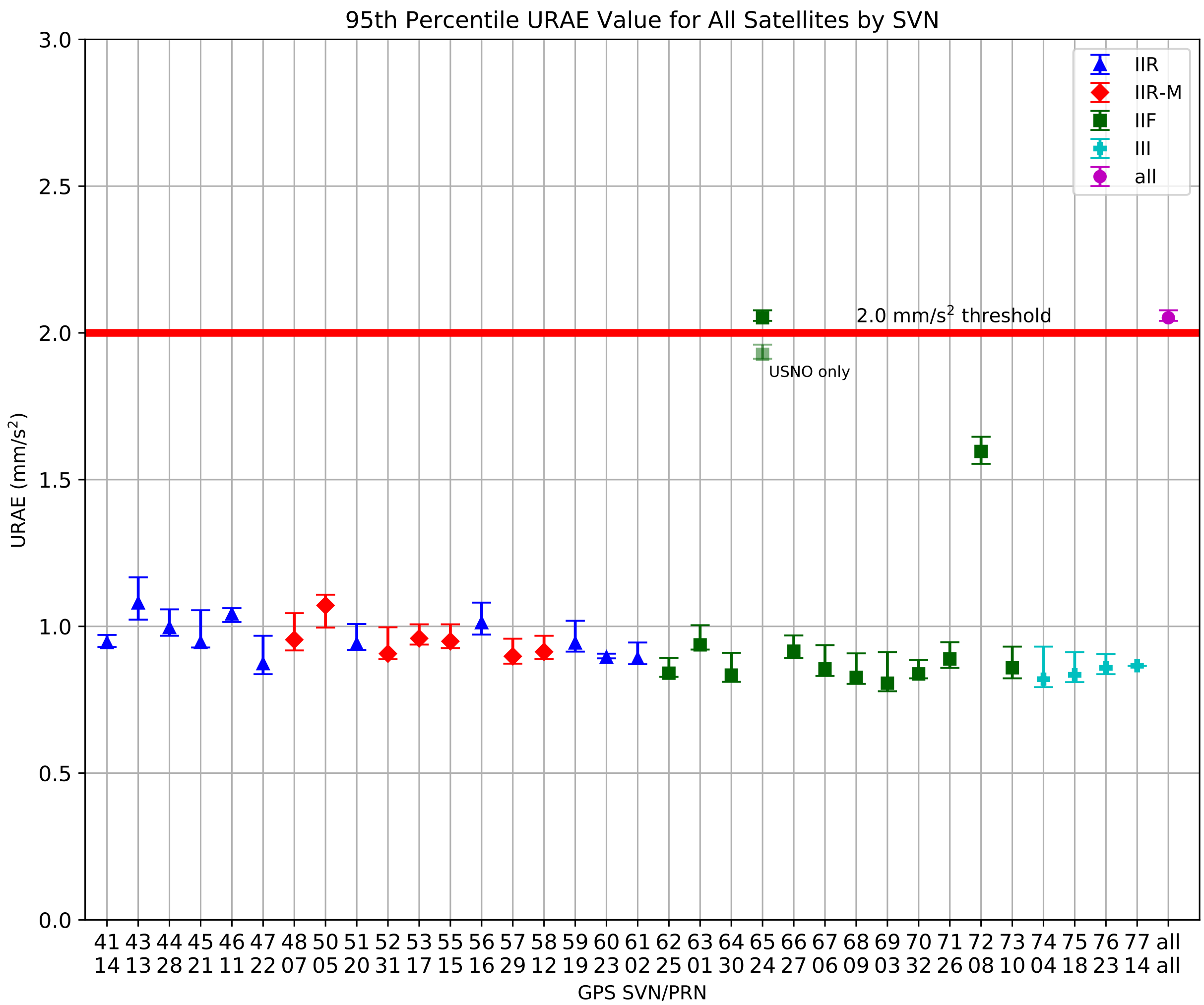


Figure 3.12: Range of the Monthly URAE 95th Percentile Values for All SVs

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 along the vertical axis. The minimum and maximum of the monthly 95th percentile URAE for 2020 are shown by whiskers on the vertical bars. Color distinguishes between the Block IIR, Block IIR-M, Block IIF, and GPS III SVs. The red horizontal line at 2.0 mm/s^2 indicates the upper bound given by the SPSPS20 Section 3.4 performance metric. The marker for "all" represents the monthly 95th percentile values across all satellites. The marker for SVN 65/PRN 24 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 Accuracy

The SPS PS provides the following assertion regarding the UTC offset error (UTCOE) Accuracy:

- *"$\leq$ 30 nsec 95% Global Statistic UTCOE 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 UTCOE 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 truth information was provided by the 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 truth values.

The selection and averaging algorithms are a key part of this process. The global statistic at each 15 minute epoch is determined by evaluating the UTCOE 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 UTCOE 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 95^{th} 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 legacy navigation message (LNAV) transmitted on L1 C/A and in message type 33 of the GPS civil navigation message transmitted on L2C and L5I. Typically the values are identical across all three sources (within the precision provided). Since 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 3.13 and 3.14 provide additional supporting information in the form of a time-history of global statistic UTCOE values at each 15 minute epoch for the year. Table 3.7 provides the results for each month of 2020. None of these values exceed the assertion of 30 nsec. Therefore the assertion is verified for 2020.

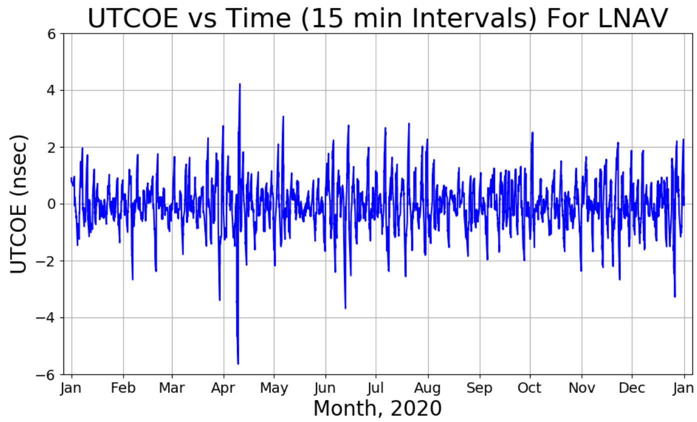


Figure 3.13: UTCOE LNAV Time Series for 2020

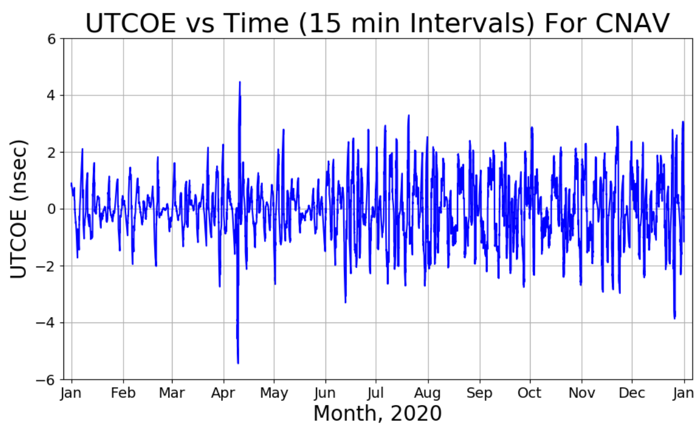


Figure 3.14: UTCOE CNAV Time Series for 2020

Table 3.7: 95^{th} Percentile Global Statistic UTCOE for 2020

Month	**95^{th}% Global Avg. UTCOE (nsec)**	
	LNAV	CNAV
Jan.	1.24	1.35
Feb.	1.66	1.46
Mar.	1.81	1.73
Apr.	2.48	2.24
May	1.60	1.84
Jun.	2.23	2.36
Jul.	2.14	2.53
Aug.	1.30	1.98
Sep.	1.42	2.20
Oct.	1.54	2.30
Nov.	1.84	2.73
Dec.	1.78	2.58

3.3 SIS Integrity

3.3.1 URE Integrity

Under the heading of SIS Integrity, the SPSPS20 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, and a worst case for a delayed alert of 6 hours.

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 SPSPS20 Section A.5.5 for a complete description.

This assertion was verified using two methods:

- The Instantaneous SIS URE values at the worst case location in view of each SV at each 30 s 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.)
- ORDs 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 URE (as described in Appendix C.2.5). Similarly, the ORD values may be incorrect due to receiver or reception issues. Therefore, all reported violations are examined manually to determine whether a violation actually occurred, and if so, the extent of the violation.

Screening the 30 s Instantaneous SIS URE values and the ORD data did not reveal any events for which this threshold was exceeded. Therefore the assertion is verified for 2020.

3.3.2 UTCOE Integrity

The SPS PS 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, a NTE tolerance of ±120 nsec, given 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. See SPSPS20 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 truth data obtained from USNO [9]. 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 2020. The value farthest from zero for the year was -5.64 nsec for LNAV and -5.45 nsec for CNAV, both during April (see Figures 3.13 and 3.14). Therefore the assertion is verified for 2020.

3.3.3 Instantaneous P_{sat} and P_{const}

The SPS PS 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 previously. The primary difference is the difference in the period of evaluation. Since there were no periods in which the SPS SIS Instantaneous URE exceeded the NTE tolerance, the value of both these assertions is 0.0, which fulfills the assertions.

3.4 SIS Continuity

3.4.1 Unscheduled Failure Interruptions

The SIS Continuity metric for single frequency L1 C/A-code is stated in SPSPS20 Table 3.6-1 as follows:

- *"$\geq$ 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.

The notion of SIS continuity is slightly more complex for an expandable slot, because multiple SVs are involved. Following SPSPS20 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.

Another point is that 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.

Three factors must be considered in looking at this metric:

1. We must establish which SVs were assigned to which slots during the period of the evaluation.
2. We must determine when SVs were not transmitting, or not transmitting a PRN available to users.
3. We must determine 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 one or more of the SVs assigned to the given slot are unhealthy in the sense of SPSPS20 Section 2.3.2.

The following specific indications were considered:

- If the health bits in navigation message subframe 1 are set to anything other than all zeros.
- If an appropriately distributed worldwide network of stations failed to collect any pseudorange data sets for a given measurement interval.

The latter case (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 provides at least two-station visibility (and at least 90% three-station visibility) with redundant receivers at each station, both continuously monitoring up to 12 SVs in view. 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. The 30 s Receiver Independent Exchange format (RINEX) [10] observation files from this network 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 L1 C/A, L1 P(Y), and L2 P(Y) 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. In addition, the 30 s IGS data collected to support the position accuracy estimates (Section 3.6.3) were examined in a similar fashion to guard against any MSN control center outages that could have led to missing data across multiple stations simultaneously. This allows us to define an epoch-by-epoch availability for each satellite. Then, for each slot, each hour in the year was examined, and if an SV occupying the slot was not available at the start of the hour, the hour was not considered as part of the evaluation of the metric. If the slot was determined to be available, then 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. After this, the Notice Advisories to Navstar Users (NANUs) effective in 2020 were reviewed to determine which of these interruptions could be considered scheduled interruptions as defined in SPSPS20 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.

Scheduled interruptions as defined in the ICD-GPS-240 [11] have a nominal notification time of 96 hours prior to the outage. Following the SPSPS20 Section 2.3.5, scheduled interruptions announced 48 hours in advance are not to be considered as contributing to the loss of continuity. So to contribute to a loss of continuity, the notification time for a scheduled interruption must occur less than 48 hours in advance of the interruption. In the case of an interruption not announced in a timely manner, the time from the start of the interruption to the moment 48 hours after notification time can be considered as a potential unscheduled interruption (for continuity purposes).

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
- FCSTEXTD - Forecast Extension
- FCSTRESCD - Forecast Rescheduled
- FCSTUUFN - Forecast Unusable Until Further Notice

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

For scheduled interruptions that extend beyond the period covered by a FCSTDV or FCSTMX NANU, the uncovered portion will be considered an unscheduled interruption. If a FCSTEXTD NANU extending the length of a scheduled interruption is published 48 hours in advance of the effective time of extension, we categorize the interruption as scheduled. It is worth reiterating that, for the computation of the metric, only those hours for which a valid SIS is available from the slot at the start of the hour are actually considered in the computation of the values.

The results of the assessment of SIS continuity are summarized in Table 3.8. 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.

To put this in perspective, there are 8760 hours in a year (8784 for a leap year). The required probability of not losing SPS SIS availability is calculated as an average over all slots in the 24-slot constellation, which implies that the maximum number of unscheduled interruptions over the year is given by $8760 \times (1 - 0.9998) \times 24 = 42$ unscheduled hours that experience interruptions. 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 3.8, across the slots in the constellation the total number of hours lost was 8. 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 0.999959. Therefore, this assertion is considered fulfilled in 2020.

Table 3.8: Probability Over Any Hour of Not Losing L1 C/A Availability Due to Unscheduled Interruption for 2020

Plane-Slot	# of Hours with the SPS SIS available at the start of the hour[b]	# of Hours with Unscheduled Interruption[c]	Fraction of Hours in Which Availability was Maintained
A1	4583	1	0.999782
A2	8778	0	1.000000
A3	8775	0	1.000000
A4	8723	1	0.999885
B1[a]	7543	0	1.000000
B2	8749	1	0.999886
B3	8778	0	1.000000
B4	8784	1	0.999886
C1	8778	0	1.000000
C2	8779	0	1.000000
C3	8781	0	1.000000
C4	7265	0	1.000000
D1	8777	0	1.000000
D2[a]	8546	1	0.999883
D3	8778	0	1.000000
D4	8774	0	1.000000
E1	1703	0	1.000000
E2	8781	0	1.000000
E3	8784	0	1.000000
E4	8784	0	1.000000
F1	8777	0	1.000000
F2[a]	8776	1	0.999886
F3	8776	0	1.000000
F4	8774	2	0.999772
All Slots	196346	8	0.999959

[a] *When 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.*

[b] *There were 8784 hours in the evaluation period.*

[c] *Number 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 other than all zeroes without a scheduled outage, or (2.) signal lost without a scheduled outage.*

3.4.2 Status and Problem Reporting Standards

3.4.2.1 Scheduled Events

The SPSPS20 makes the following assertion in Section 3.6.3 regarding notification of scheduled events affecting service:

- *"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 [11] 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 3.9 summarizes the pairs found for 2020. The two leftmost columns provide the SVN/PRN of the subject SV. The next three columns specify the NANU #, type, and date/time of the NANU for the forecast NANU. These are followed by three columns that specify the NANU #, the date/time of the NANU for 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. Notice times less than 48 hours are shown in red. The average notice time in 2020 was over 143 hours.

To meet the assertion in the performance standard, at least 95% of the values in the rightmost column of Table 3.9 should be greater than 48.0. For 2020, 33 of 34 events, 97.1%, had a notice time greater than 48 hours. Therefore, this assertion is satisified.

Multiple satellites were decommissioned in 2020. Table 3.10 provides the details on how this was represented in the NANUs.

Multiple satellites were launched and set initially usable in 2020. Table 3.11 provides details. The LAUNCH NANU for SVN 74 (NANU 2019159) was released on 22 Oct 2019, however SVN 74 was launched on 23 Dec 2018 and underwent extensive testing prior to the LAUNCH and USABINIT NANUs (see GENERAL NANU 2019001). Similarly, the LAUNCH NANU for SVN 75 was released in 2020, while the satellite was launched in 2019.

Table 3.9: Scheduled Events Covered in NANUs for 2020

SVN	PRN	Forecast NANU			Summary NANU (FCSTSUMM)			Notice
		NANU #	TYPE	Release Time	NANU #	Release Time	Start Of Outage	(hrs)
68	09	2020001	FCSTDV	03 Jan 1931Z	2020003	10 Jan 0213Z	09 Jan 2113Z	145.70
44	28	2020002	FCSTDV	08 Jan 1930Z	2020005	17 Jan 0150Z	16 Jan 1958Z	192.47
71	26	2020006	FCSTDV	07 Feb 1557Z	2020008	13 Feb 2200Z	13 Feb 1806Z	146.15
46	11	2020007	FCSTDV	13 Feb 1837Z	2020009	21 Feb 0224Z	20 Feb 1946Z	169.15
52	31	2020013	FCSTDV	16 Mar 1412Z	2020014	19 Mar 1646Z	19 Mar 1049Z	68.62
67	06	2020016	FCSTDV	16 Apr 2213Z	2020017	24 Apr 0355Z	23 Apr 2152Z	167.65
45	21	2020018	FCSTDV	04 May 2203Z	2020020	08 May 0745Z	08 May 0124Z	75.35
75	18	2020019	FCSTDV	07 May 1634Z	2020023	14 May 2310Z	14 May 1557Z	167.38
47	22	2020021	FCSTDV	12 May 2103Z	2020024	22 May 1232Z	22 May 0511Z	224.13
62	25	2020022	FCSTDV	13 May 1509Z	2020025	28 May 1743Z	28 May 1134Z	356.42
63	01	2020026	FCSTDV	29 May 2202Z	2020027	11 Jun 1958Z	04 Jun 2310Z	145.13
69	03	2020028	FCSTDV	19 Jun 2025Z	2020029	26 Jun 0957Z	26 Jun 0448Z	152.38
57	29	2020030	FCSTDV	01 Jul 2017Z	2020032	09 Jul 1600Z	09 Jul 0948Z	181.52
74	04	2020035	FCSTMX	10 Jul 1952Z	2020036	14 Jul 1811Z	14 Jul 1212Z	88.33
56	16	2020037	FCSTDV	31 Jul 1840Z	2020038	07 Aug 0401Z	06 Aug 2137Z	146.95
43	13	2020039	FCSTDV	13 Aug 1842Z	2020040	21 Aug 1737Z	21 Aug 0948Z	183.10
70	32	2020041	FCSTDV	16 Sep 2045Z	2020044	23 Sep 0237Z	22 Sep 2136Z	144.85
62	25	2020045	FCSTMX	25 Sep 1538Z	2020049	02 Oct 2335Z	01 Oct 1916Z	147.63
59	19	2020047	FCSTDV	01 Oct 2208Z	2020051	08 Oct 1503Z	08 Oct 0847Z	154.65
63	01	2020052	FCSTMX	12 Oct 1617Z	2020055	16 Oct 1645Z	16 Oct 1219Z	92.03
64	30	2020054	FCSTMX	15 Oct 1716Z	2020056	20 Oct 1705Z	20 Oct 1233Z	115.28
61	02	2020053	FCSTDV	15 Oct 1706Z	2020058	22 Oct 2036Z	22 Oct 1312Z	164.10
65	24	2020061	FCSTRESCD	26 Oct 1404Z	2020062	27 Oct 1930Z	27 Oct 1437Z	24.55
66	27	2020059	FCSTMX	23 Oct 1555Z	2020063	28 Oct 1714Z	28 Oct 1236Z	116.68
53	17	2020060	FCSTDV	23 Oct 2108Z	2020066	30 Oct 0438Z	29 Oct 2240Z	145.53
67	06	2020064	FCSTMX	28 Oct 2128Z	2020067	02 Nov 1627Z	02 Nov 1255Z	111.45
68	09	2020065	FCSTMX	30 Oct 0314Z	2020068	04 Nov 1642Z	04 Nov 1303Z	129.82
69	03	2020070	FCSTMX	04 Nov 2344Z	2020073	09 Nov 1940Z	09 Nov 1639Z	112.92
70	32	2020071	FCSTMX	05 Nov 1923Z	2020074	10 Nov 1538Z	10 Nov 1213Z	112.83
64	30	2020069	FCSTDV	04 Nov 2054Z	2020078	13 Nov 0528Z	13 Nov 0022Z	195.47
71	26	2020076	FCSTMX	12 Nov 1914Z	2020081	17 Nov 0027Z	16 Nov 2038Z	97.40
45	21	2020079	FCSTDV	13 Nov 1536Z	2020082	18 Nov 1453Z	18 Nov 0716Z	111.67
72	08	2020080	FCSTMX	13 Nov 1542Z	2020084	20 Nov 1550Z	20 Nov 1245Z	165.05
73	10	2020083	FCSTMX	18 Nov 2120Z	2020085	23 Nov 2311Z	23 Nov 2008Z	118.80
Average Notice Period								143.27

Table 3.10: Decommissioning Events Covered in NANUs for 2020

SVN	PRN	FCSTUUFN NANU		DECOM NANU			Notice
		NANU #	Release Time	NANU #	Release Time	End of Unusable Period	(hrs)
60	23	2020010	04 Mar 2041Z	2020012	12 Mar 0131Z	09 Mar 1919Z	118.63
41	14	2020031	07 Jul 1654Z	2020034	09 Jul 2224Z	09 Jul 1816Z	49.37
46	11	2020072	06 Nov 0019Z	2020075	11 Nov 0012Z	10 Nov 1514Z	110.92
Average Notice Period							92.97

Table 3.11: Launch Events Covered in NANUs for 2020

SVN	PRN	LAUNCH NANU		USABINIT NANU	
		NANU #	Launch Time	NANU #	Start Time
74	04	2019159	23 Dec 1351Z (2018)	2020004	13 Jan 1734Z
75	18	2020011	21 Aug 1306Z (2019)	2020015	01 Apr 1945Z
76	23	2020033	30 Jun 2010Z (2020)	2020046	01 Oct 1627Z
77	14	2020077	05 Nov 2324Z (2020)	2020086	02 Dec 0107Z

3.4.2.2 Unscheduled Outages

The SPS PS 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 3.12 provides a list of the unscheduled outages found in the NANU information for 2020. 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 3.8. The next two columns provide the NANU # and date/time of the UNUSUFN NANU. These are followed by three columns that specify the NANU #, the date/time of the NANU for 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 minutes). Values in the final column are shown in red if they have a lag time of greater than 60 minutes. The rate of unscheduled outages was comparable to that of previous years.

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, for events listed in Table 3.12 the threshold time was met for all events and the nominal time was met for both events.

Table 3.12: Unscheduled Events Covered in NANUs for 2020

SVN	PRN	Plane-Slot[a]	UNUSUFN NANU		UNUSABLE/UNUNOREF NANU			Lag Time (minutes)
			NANU #	Release Time	NANU #	Release Time	Start Of Event	
74	04	F4	2020042	20 Sep 0017Z	2020043	20 Sep 0542Z	20 Sep 0031Z	-14.00[b]
48	07	A4	2020087	23 Dec 0336Z	2020090	25 Dec 1756Z	23 Dec 0325Z	11.00
Average Lag Time								11.00

[a] *If an SV is not in a defined slot, only the plane is specified.*
[b] *NANU 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 makes the following assertions in Section 3.7.1:

- *"$\geq$ 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"*
- *"$\geq$ 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 3.13. 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.

Regardless of the individual slot availabilities, the average availability for the constellation was 0.991, which is above the threshold of 0.957. Therefore the assertion being evaluated in this section was met.

Table 3.13: Per-Slot Availability for 2020

Plane-Slot	# Missing Epochs[b]	Availability
A1	674	0.999361
A2	711	0.999325
A3	1121	0.998937
A4	7297	0.993077
B1[a]	1667	0.998419
B2	4240	0.995978
B3	697	0.999339
B4	44	0.999958
C1	725	0.999312
C2	553	0.999475
C3	366	0.999653
C4	182338	0.827017
D1	867	0.999177
D2[a]	28795	0.972682
D3	757	0.999282
D4	1101	0.998955
E1	974	0.999076
E2	364	0.999655
E3	0	1.000000
E4	0	1.000000
F1	968	0.999082
F2[a]	977	0.999073
F3	1057	0.998997
F4	1284	0.998782
All Slots	237577	0.990609

[a] *When 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.*

[b] *For each slot there were 1054080 total 30 s epochs in the evaluation period.*

3.5.2 Constellation Availability

The SPSPS20 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 2020. Following a literal reading of the requirement, the number of SVs broadcasting a healthy SIS was examined for each measurement interval and assigned to the correct slot. 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 healthy SVs were found: one in each of the two portions of the expanded slot. If the count of occupied slots was greater than 20, the measurement interval was counted as a 1; otherwise the measurement interval was assigned a zero. The sum of the 1 values was then divided by the total number of measurement intervals. The value for 2020 is 1.00. 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 the count of occupied slots and for the number of SVs. The daily averages as a function of time are shown in Figure 3.15. As is clear, the number of occupied slots always exceeded 21.

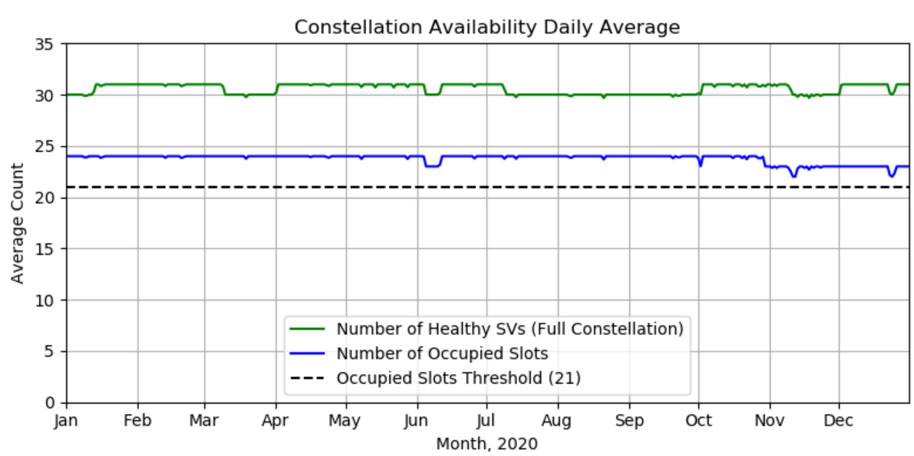


Figure 3.15: Daily Average Number of Occupied Slots

3.5.3 Operational Satellite Counts

Table 3.7-3 of the SPSPS20 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 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 2020, thus meeting the assertion. However, to evaluate this more explicity, the almanac status was examined directly. The process consisted of selecting an almanac for each day in 2020. IS-GPS-200 Section 20.3.3.5.1.3 [2] assigns a special meaning to the SV health bits in the almanac's subframe 4 page 25 and subframe 5 page 25 (Data ID 51 and 63). When these bits are set to all ones it indicates "the SV which has that ID is not available, and there might be no data regarding that SV in that page of subframes 4 and 5..." Given this definition, the process examines the subframe 4 and 5 health bits for the individual SVs and counts the number of SVs for which the health bits are other than "all ones". The results are shown in Figure 3.16. This plot is very similar to the full constellation healthy satellite count shown in Figure 3.15. The almanac health data are not updated as frequently as those in subframe 1. As a result, the plot in Figure 3.16 contains only integer values. Therefore, on days when it appears the operational SV count is lower than the number of healthy SVs in the constellation, these reflect cases where an SV was set unhealthy for a small portion of the day. In Figure 3.15, such effects are averaged over the day, yielding a higher availability.

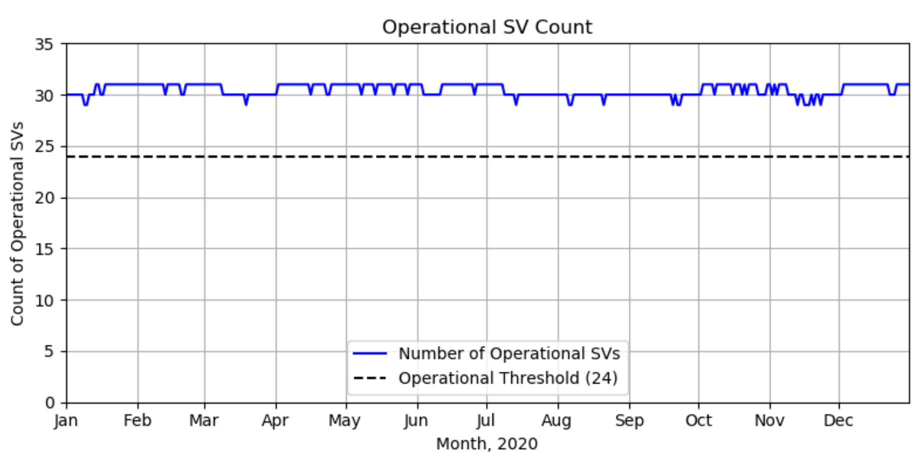


Figure 3.16: Count of Operational SVs by Day for 2020

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 SVs that are observed. 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 a sufficient number of accurate signals with acceptable geometric diversity. The former requirement is addressed by the URE assertions in Section 3.4 of the performance standards. The requirement for geometric diversity is addressed by the PDOP assertions in Section 3.8.1 of the SPSPS20.

Section 3.6.1.1 provides the evaluation of the PDOP assertions stated in SPSPS20. Section 3.6.1.2 provides additional supporting information beyond the stated assertion and includes results specific to the various types of DOP to better explain how well the constellation meets the assertion.

3.6.1.1 PDOP Availability

Given representative user conditions and considering any 24 hour interval the SPSPS20 calls for:

- *"$\geq$ 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 Section 3.8, a 5° minimum elevation angle is used for this evaluation.

These assertions were verified empirically throughout 2020 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 km $\times$ 111 km (roughly $1° \times 1°$ at the Equator). The time started at 0000Z each day and stepped through the entire day at one minute intervals (1440 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) [12].

The PDOP values were formed using the traditional PDOP algorithm [13], 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 receiver 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 ≤ 6. 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.

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 2020.

Once the PDOPs had been computed across all grid points, for each of the 1440 time increments during the day, the percentage of time PDOP ≤ 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 ≤ 6 was computed.

Table 3.14 summarizes the results of this analysis for the configurations of all SVs available. The second column ("Average daily % over 2020") provides the values for the assertions. The additional 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 2020.

Table 3.14: Summary of PDOP Availability

Metric	Average daily % over 2020	Minimum daily % over 2020
$\geq$ 98% Global Average PDOP ≤ 6	$>$ 99.999	99.997
$\geq$ 88% Worst site PDOP ≤ 6	99.902	98.611

In addition to verifying the assertion, several additional analyses go beyond the direct question and speak to the matter of how well the system is performing on a more granular basis. The remainder of this chapter describes those analyses and results.

3.6.1.2 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, $\langle DOP\rangle(day)$, is defined to be

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

Another measure of performance is the average DOP over the day at the worst site, $\langle DOP\rangle_{worst\,site}$. 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.

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

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

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

Given that the $\langle DOP\rangle_{worst\,site}(day)$ is most closely related to the worse 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 2020, both $\langle DOP\rangle_{worst\,site}(day)$ and $\langle DOP_{worst\,site}\rangle(day)$ satisfy the SPS PS assertions.

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

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

This serves as a sanity check on the DOP results in general 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 $\langle DOP\rangle_{worst\,site}$ 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 $\langle DOP\rangle_{worst\,site}$ values. These values are presented in Table 3.15, with values for 2017 through 2019 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 3.15 are the annual means of the global average number of satellites visible to grid cells on a 111 km × 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, it 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 3.15 the values are very similar across all four years.

Table 3.15: Additional DOP Annually-Averaged Visibility Statistics for 2017 – 2020

	⟨DOP⟩				**⟨DOP⟩$_{\textbf{worst site}}$**			
	2017	**2018**	**2019**	**2020**	**2017**	**2018**	**2019**	**2020**
Horizontal DOP	0.83	0.84	0.84	0.84	0.94	0.95	0.96	0.95
Vertical DOP	1.35	1.36	1.36	1.35	1.68	1.70	1.70	1.70
Time DOP	0.78	0.79	0.79	0.79	0.89	0.91	0.90	0.90
Position DOP	1.59	1.60	1.60	1.60	1.83	1.86	1.86	1.85
Geometry DOP	1.77	1.79	1.79	1.78	2.04	2.07	2.06	2.06
Number of visible SVs	10.49	10.42	10.42	10.32	5.95	5.32	5.02	5.77

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 98^{th} percentile of the daily globally averaged PDOP values. Similarly, calculations can be done for $\langle DOP \rangle_{worst\, site}$ criteria of having the PDOP ≤ 6 greater than 88% of the time. Table 3.16 presents these values for 2020 and the previous three years.

Table 3.16: Additional PDOP Statistics

	2017	**2018**	**2019**	**2020**
% of Days with the $\langle PDOP \rangle \leq 6$	100.00	100.00	100.00	100.00
% of Days with the $\langle PDOP \rangle$ at Worst Site ≤ 6	100.00	100.00	100.00	100.00
98^{th} Percentile of $\langle PDOP \rangle$	1.60	1.64	1.62	1.63
88^{th} Percentile of $\langle PDOP \rangle_{worst\, site}$	1.84	1.87	1.89	1.88

Table 3.16 shows that the average DOP values for 2020 are nearly identical to the previous three years.

Behind the statistics are the day-to-day variations. Figure 3.17 provides a time history of PDOP metrics considering all satellites for 2020. Three metrics are plotted:

- Daily Global Average PDOP: $\langle PDOP \rangle$
- Average Worst Site PDOP: $\langle PDOP \rangle_{worst\,site}$
- Average PDOP at Worst Site: $\langle PDOP_{worst\,site} \rangle$

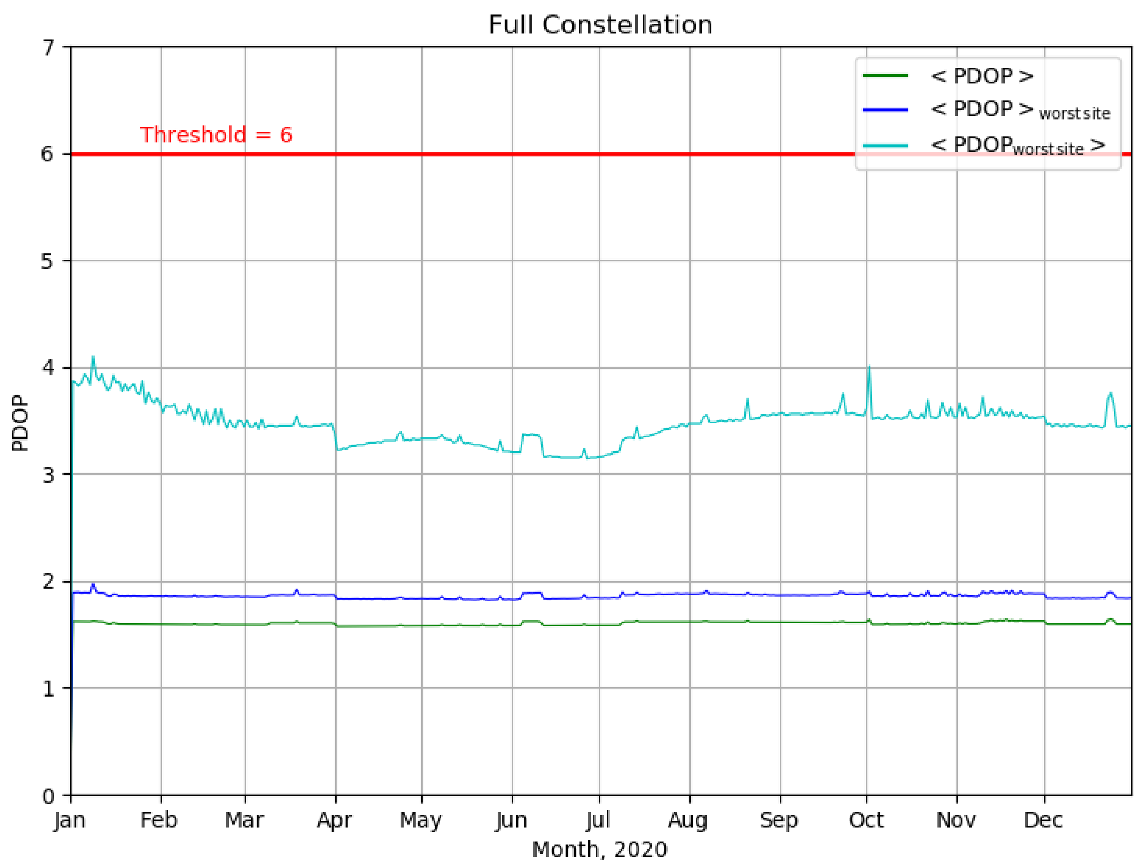


Figure 3.17: Daily PDOP Metrics Using All SVs for 2020

3.6.2 Position Service Availability

The positioning and timing availability standards are stated in Table 3.8-2 of SPSPS20 as follows:

- *"≥ 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"*

The conditions and constraints associated with the standards include the specification of a 15 m horizontal 95th percentile threshold and a 33 m vertical 95th percentile threshold.

These are derived values as described in the sentence preceding SPSPS20 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 SPSPS20 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 SPSPS20 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 are derived values as described in the sentence preceding SPSPS20 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 for a set of continuously operating stations from two networks (MSN and IGS). The process used by ARL:UT is described in Appendix C.5.

The process generates position solutions using both NGA and IGS observation data (see Figure 1.1) and using both a simplistic approach with no data editing and a receiver autonomous integrity monitoring (RAIM) approach.

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 values across all stations. In the second set, the worst site is determined on a day-to-day basis and the worst site 95^{th} percentile values are computed.

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 2880 solutions per station per day. Truth positions for the IGS stations were taken from the weekly Station Independent Exchange format (SINEX) files. Truth locations for the NGA stations were taken from station locations defined as part of the latest WGS 84 reference frame [14] with corrections for station velocities applied.

Residuals between estimated locations and the truth 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 3.18-3.21 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 2020. 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 truth 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:

- Mean & Median values - The means and medians of the position residuals given in Table 3.17 are nearly identical for the NGA data sets, suggesting that if there are any 30 s position residual outliers, they are few in number and not too large. For the IGS data sets, the means for both the solutions are only slightly larger than the medians, indicating the presence of some outliers, but not a great many. This is consistent with the outliers observed in Figure 3.18 and Figure 3.19.

- Maximum values and Standard Deviation - The values shown in Table 3.17 for the IGS data sets are quite a bit larger than the corresponding values for the NGA data sets. Once again, this suggests that there are some large 30 s position residuals in the epoch-by-epoch results for these data sets.

- Differences between NGA and IGS results - The mean magnitude of the position residual as reported in Table 3.17 is slightly smaller for the NGA stations than for the IGS stations. 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, the data are derived from full-code tracking, 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 differences likely account for the greater variability in the results derived from the IGS data sets.

Table 3.17: Daily Average Position Errors for 2020

Statistic	**Data Editing**	**Horizontal**		**Vertical**	
		IGS	**NGA**	**IGS**	**NGA**
Mean (m)	RAIM	1.26	1.09	2.13	1.45
	None	1.28	1.10	2.19	1.46
Median (m)	RAIM	1.24	1.09	2.10	1.45
	None	1.26	1.09	2.12	1.45
Maximum (m)	RAIM	2.18	1.23	4.14	1.67
	None	2.08	1.24	4.63	1.68
Std. Dev. (m)	RAIM	0.11	0.04	0.22	0.05
	None	0.12	0.04	0.31	0.06

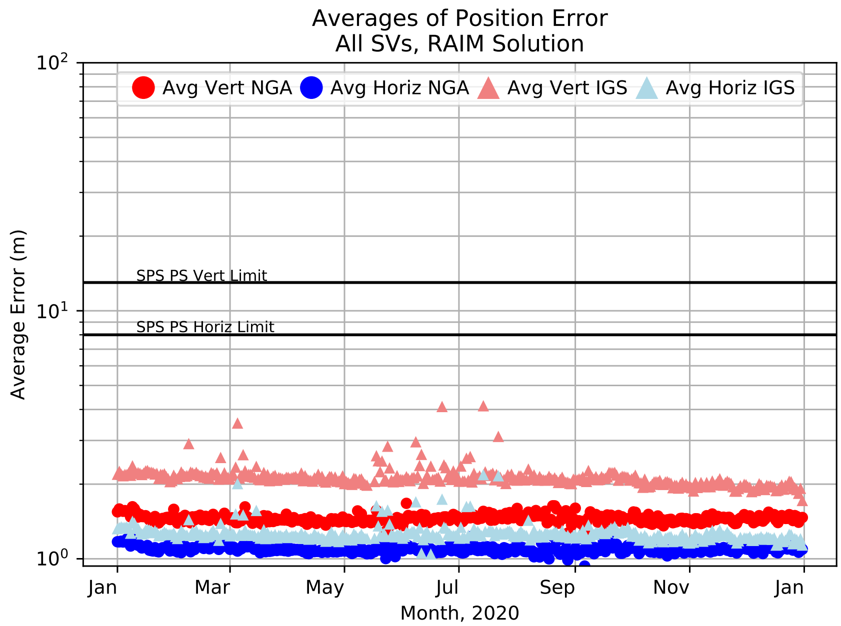


Figure 3.18: Daily Averaged Position Residuals Computed Using a RAIM Solution

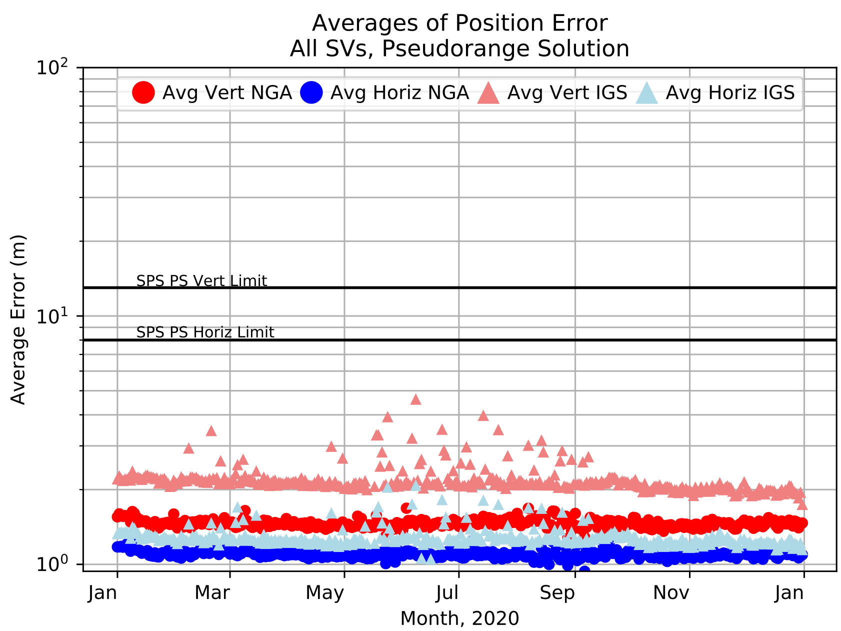


Figure 3.19: Daily Averaged Position Residuals Computed Using No Data Editing

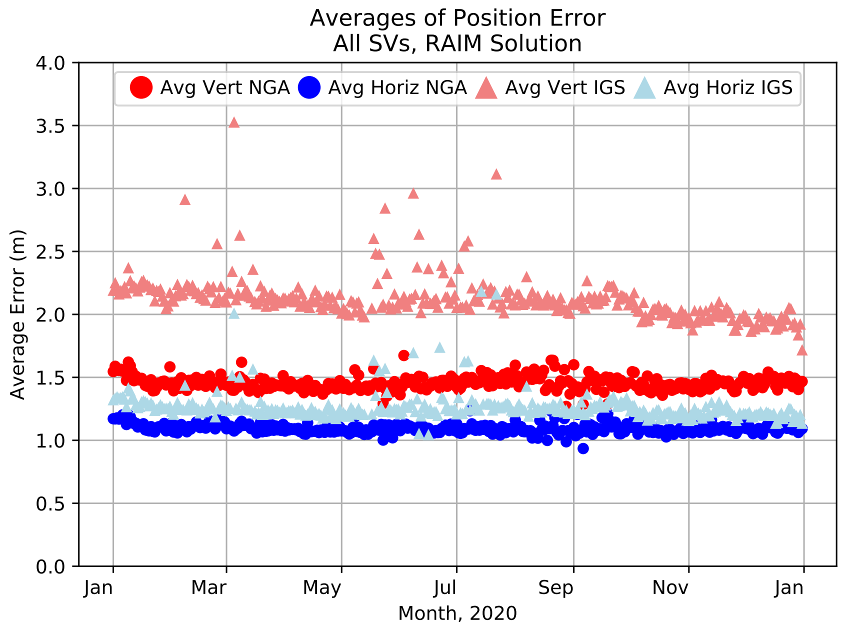


Figure 3.20: Daily Averaged Position Residuals Computed Using a RAIM Solution (enlarged)

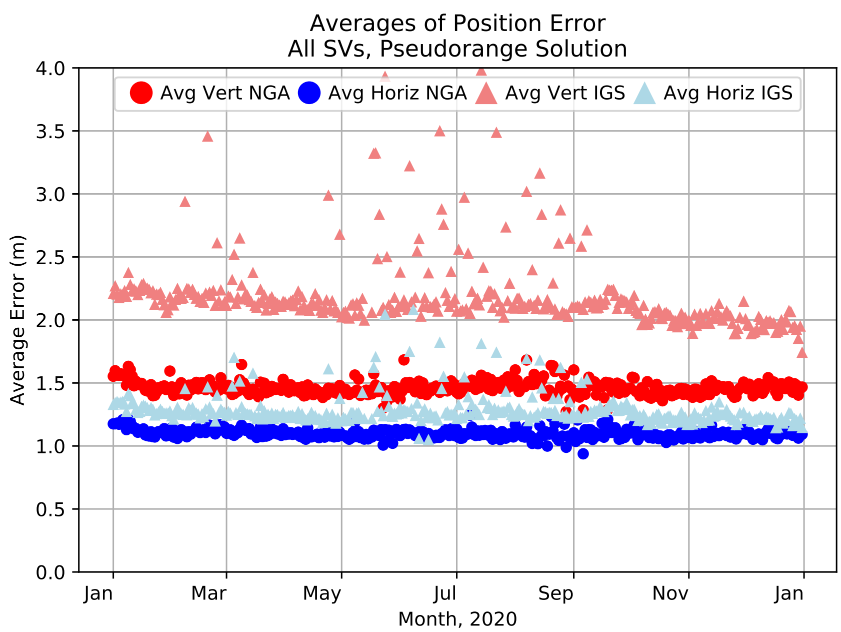


Figure 3.21: Daily Averaged Position Residuals Computed Using No Data Editing (enlarged)

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 3.22-3.25 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. Some general observations on the results are included following the tables.

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 3.22-3.25 and Table 3.18 regarding the worst site 95th percentile position solutions.

- Comparison to threshold - 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.

- Comparison between processing options - For the NGA data sets, the statistics between the RAIM and pseudorange solutions are nearly identical. For the IGS data sets, the statistics for the vertical solutions are nearly identical; however, for the horizontal data sets the mean is nearly twice as bad for the pseudorange solution. The maximum and std. dev. are also much worse. This again indicates the importance of data editing in position processing.

Table 3.18: Daily Worst Site 95th Percentile Position Errors for 2020

Statistic	Data Editing	Horizontal		Vertical	
		IGS	NGA	IGS	NGA
Mean (m)	RAIM	3.71	2.88	6.85	4.21
	None	7.81	2.90	7.00	4.22
Median (m)	RAIM	3.52	2.88	6.97	4.10
	None	3.59	2.90	7.02	4.13
Maximum (m)	RAIM	29.54	4.26	31.41	7.03
	None	108.81	4.26	32.18	7.03
Std. Dev. (m)	RAIM	2.17	0.26	1.91	0.62
	None	15.48	0.27	2.41	0.62

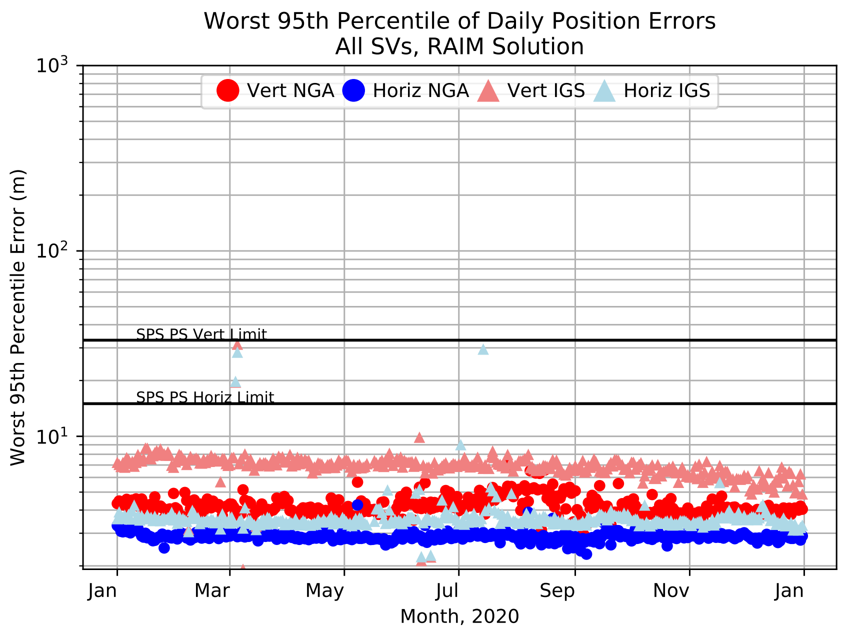


Figure 3.22: Worst Site 95th Daily Averaged Position Residuals Computed Using a RAIM Solution

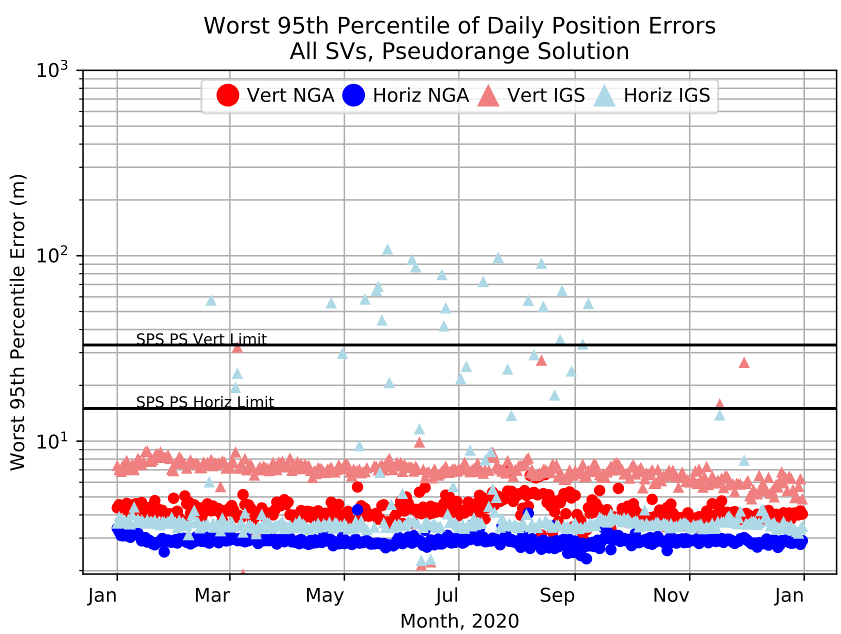


Figure 3.23: Worst Site 95th Daily Averaged Position Residuals Computed Using No Data Editing

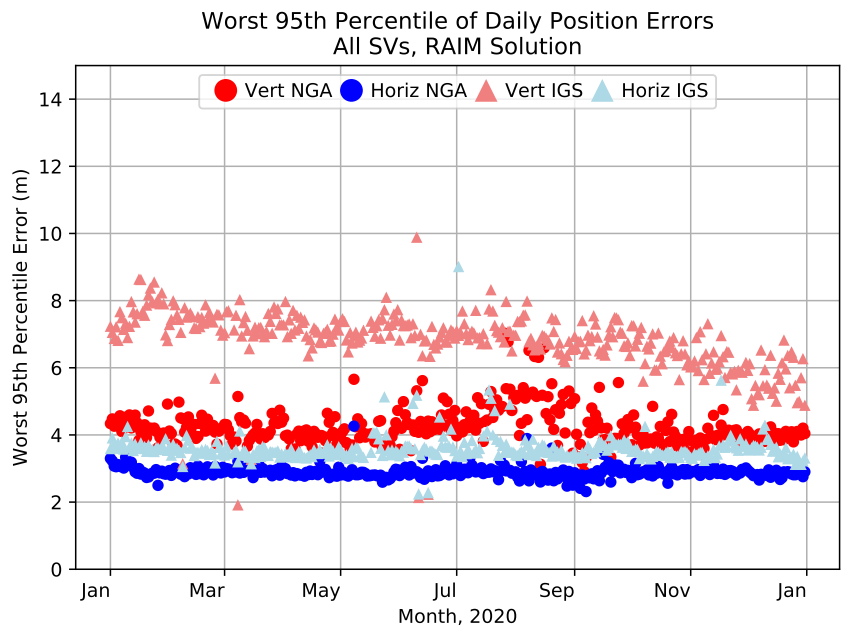


Figure 3.24: Worst Site 95th Daily Averaged Position Residuals Computed Using a RAIM Solution (enlarged)

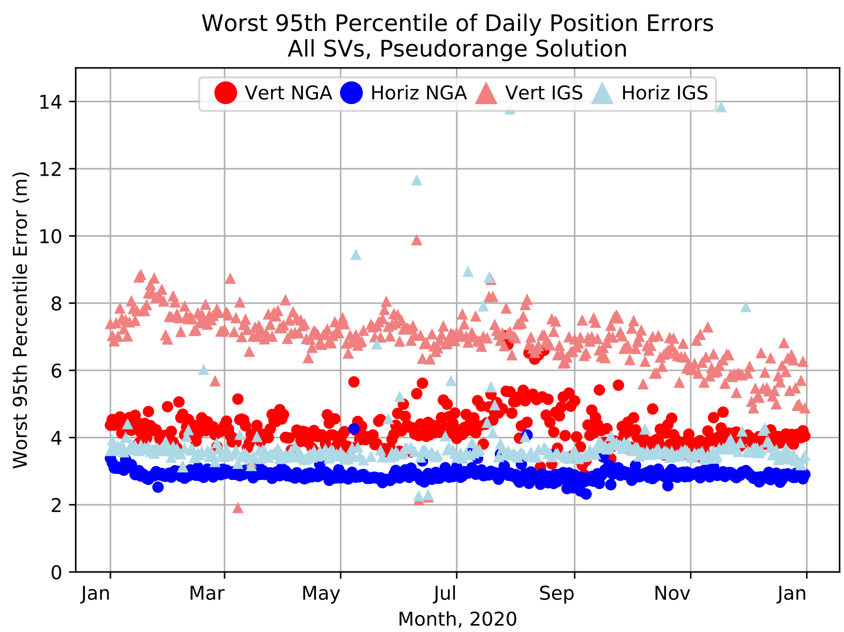


Figure 3.25: Worst Site 95th Daily Averaged Position Residuals Computed Using No Data Editing (enlarged)

3.6.4 Time Accuracy

The timing accuracy standard is stated in Table 3.8-3 of SPSPS20 as follows:

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

Conditions and Constraints:

- *Defined for a time transfer solution meeting the representative user conditions*
- *Standard based on a measurement interval of 24 hours averaged over all points in the service volume.*

The equation for time transfer accuracy relative to UTC(USNO) in GPS is found in the SPSPS20, Appendix B.2.2.

$$\text{UUTCE} = \sqrt{(\text{UERE} * \text{TTDOP}/c)^2 + (\text{UTCOE})^2)} \tag{3.6.1}$$

Time transfer dilution of precision (TTDOP) is $1/\sqrt{\text{N}}$, where N is the number is satellites visible to the user[1]. The User UTC(USNO) Error (UUTCE) calculation was performed for each day of the year.

This computation was done only for satellites that meet the criteria of: healthy, trackable, operational, and have 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 3.26). 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 1100 km.

Statistics were performed for each day over the grid of 425 points and time step of 15 minutes, resulting in 40800 points per day to determine the 95$^{\text{th}}$ percentile UUTCE value.

The computation steps are:

1. Compute satellite positions for each time point in 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 (UTCO_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 $\text{UTCOE}_i = \text{UTCO}_i$ - USNO, where USNO is the daily truth 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 40800 UUTCE values for the day, find 95% containment of all values.

[1] *as 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 3.27. All of these results are well below 30 nsec. Therefore this assertion is met.

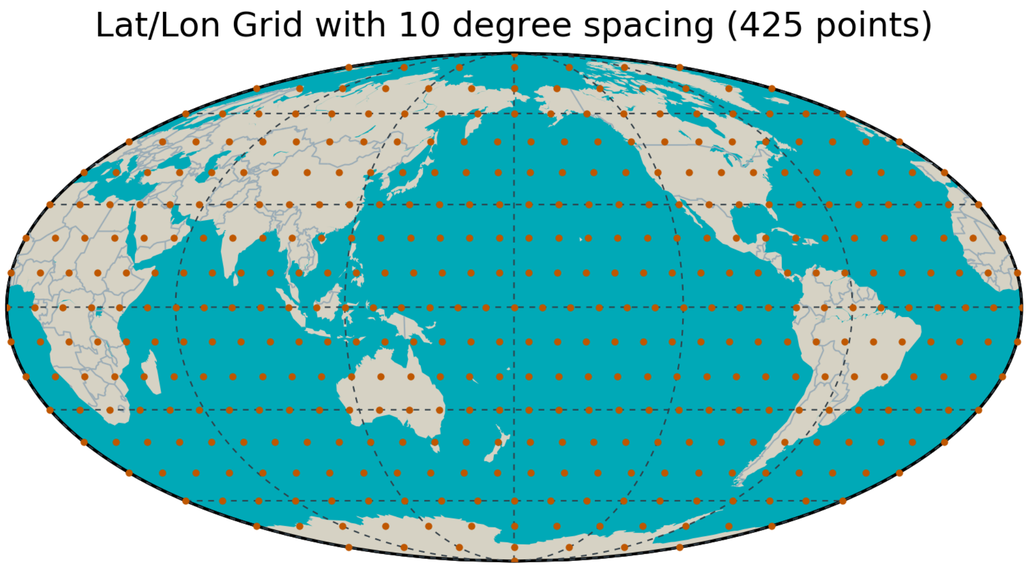


Figure 3.26: 10° Grid for UUTCE Calculation

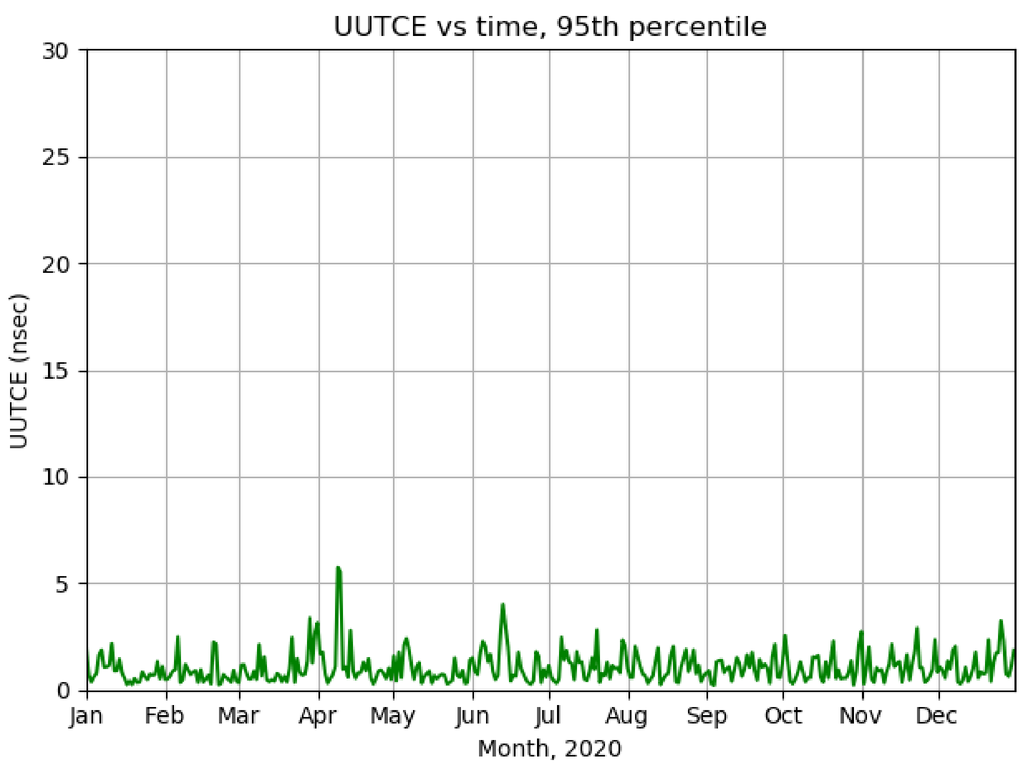


Figure 3.27: UUTCE 95th Percentile Values

Appendix A

Additional Results of Interest

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 2020. There are typically 13 unique messages per day for each SV. This leads to approximately 4750 unique messages for each year for an SV.

Table A.1 presents a summary of health bit usage in the ephemerides broadcast during 2020. 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 count of 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. Only two unique health settings were observed throughout 2020: binary 000000_2 (0x00) and binary 111111_2 (0x3F).

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 2020	Average # Subframe 1 per Operational Day
		0x3F	0x00		0x3F	0x00		
41	14	3	2490	2493	0.1	99.9	191	13.1
43	13	5	4767	4772	0.1	99.9	366	13.0
44	28	4	4802	4806	0.1	99.9	366	13.1
45	21	9	4770	4779	0.2	99.8	366	13.1
46	11	5	4098	4103	0.1	99.9	315	13.0
47	22	5	4768	4773	0.1	99.9	366	13.0
48	07	35	4742	4777	0.7	99.3	366	13.1
50	05	0	4767	4767	0.0	100.0	366	13.0
51	20	0	4765	4765	0.0	100.0	366	13.0
52	31	4	4761	4765	0.1	99.9	366	13.0
53	17	4	4768	4772	0.1	99.9	366	13.0
55	15	0	4761	4761	0.0	100.0	366	13.0
56	16	4	4769	4773	0.1	99.9	366	13.0
57	29	4	4772	4776	0.1	99.9	366	13.0
58	12	0	4770	4770	0.0	100.0	366	13.0
59	19	4	4761	4765	0.1	99.9	366	13.0
60	23	29	898	927	3.1	96.9	71	13.1
61	02	5	4762	4767	0.1	99.9	366	13.0
62	25	21	4758	4779	0.4	99.6	366	13.1
63	01	92	4685	4777	1.9	98.1	366	13.1
64	30	6	4769	4775	0.1	99.9	366	13.0
65	24	3	4884	4887	0.1	99.9	366	13.4
66	27	3	4768	4771	0.1	99.9	366	13.0
67	06	8	4774	4782	0.2	99.8	366	13.1
68	09	7	4767	4774	0.1	99.9	366	13.0
69	03	5	4774	4779	0.1	99.9	366	13.1
70	32	6	4766	4772	0.1	99.9	366	13.0
71	26	5	4764	4769	0.1	99.9	366	13.0
72	08	2	4809	4811	0.0	100.0	366	13.1
73	10	2	4768	4770	0.0	100.0	366	13.0
74	04	3	4596	4599	0.1	99.9	354	13.0
75	18	5	3547	3552	0.1	99.9	275	12.9
76	23	0	1176	1176	0.0	100.0	92	12.8
77	14	0	387	387	0.0	100.0	30	12.9
All SVs		288	145983	146271	0.2	99.8	366	399.6

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 a 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, or time (PVT) solutions for autonomous users; however, there is an impact in terms of increased operations tempo at 2nd Space Operations Squadron (2 SOPS).

Note that there is no need for a GPS receiver to refer to AOD in any PVT computation other than the optional application of the navigation message correction table (NMCT). (See IS-GPS-200 Section 20.3.3.5.1.9 for a description of the NMCT.) The AOD is computed here to validate that the operators at 2 SOPS are maintaining the URE accuracy with a normal operational tempo.

The daily average AOD throughout 2020 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 GPS III average is shown from October to the end of the year corresponding the time from which at least three GPS III SVs were available to average.

The average AOD is generally constant throughout 2020, which indicates that any variations in the URE results discussed earlier are not due to changes in operations tempo at 2 SOPS.

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

	Average Age of Data (hrs)			
	2017	**2018**	**2019**	**2020**
Full Constellation	12.1	12.1	12.0	12.0
Block IIR/IIR-M	12.1	12.1	12.0	12.0
Block IIF	12.1	12.1	12.0	11.9
GPS III	–	–	–	11.9

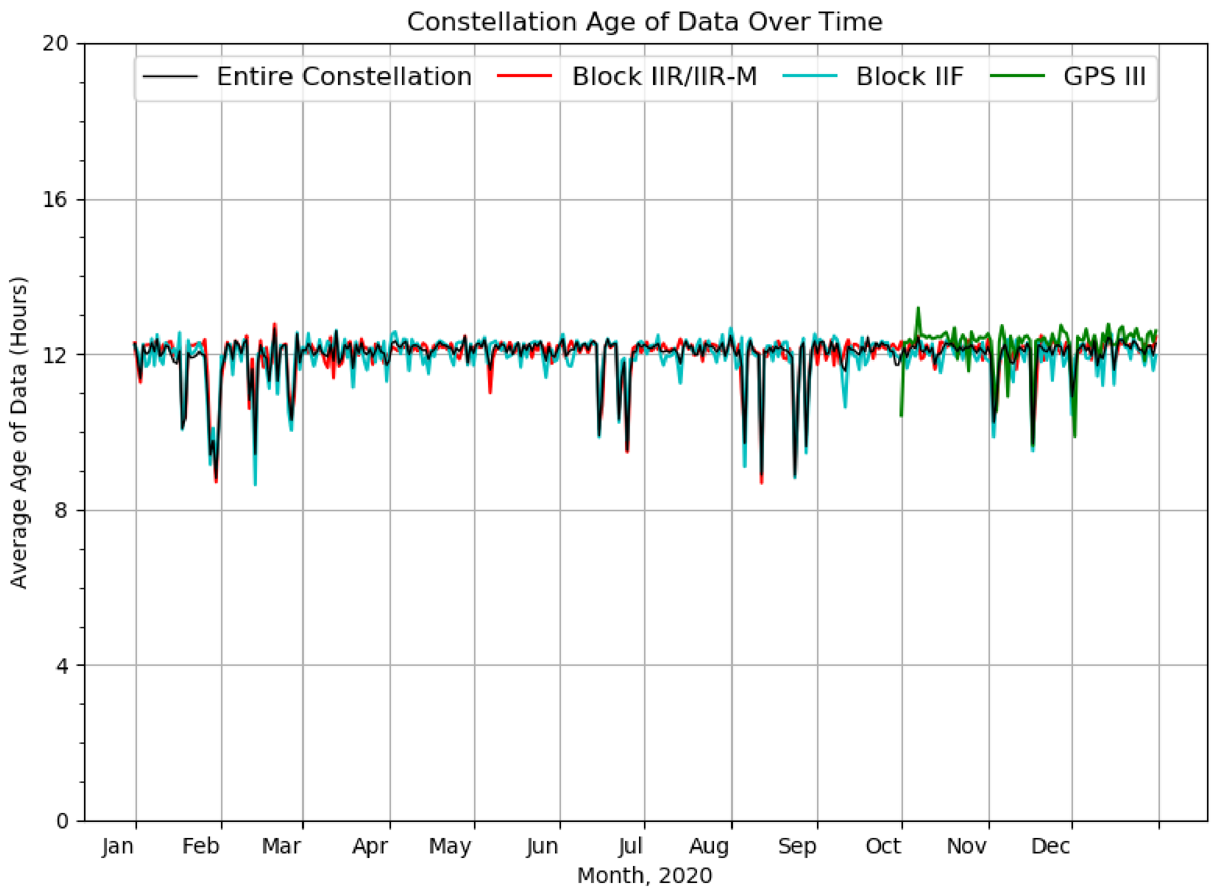


Figure A.1: Constellation Age of Data for 2020

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 URA index. Only periods in which the SV was transmitted a healthy indication are included. SVs that were operational only part of the year have lower total values.

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

Analysis of the integrity assured URA (IAURA) value derived from the CNAV data requires a slightly different approach. Since the IAURA is a continuous function, we computed the IAURA value at each 30s epoch, then binned those values corresponding to the range of URA values in IS-GPS-200 Section 20.3.3.3.1.3. That is to say, URA Index 1 has a range of 2.40 to 3.40 m; therefore IAURA values that fall into that range are assigned to Bin 1. IAURA 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 an IAURA 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. These results are obviously different than the results in Figure A.2 with far more results in higher bins. The behavior changed in the middle of the year such that CNAV and LNAV became consistent. Figure A.4 presents the same results, but limited to the second half of 2020. These results are consistent with Figure A.2.

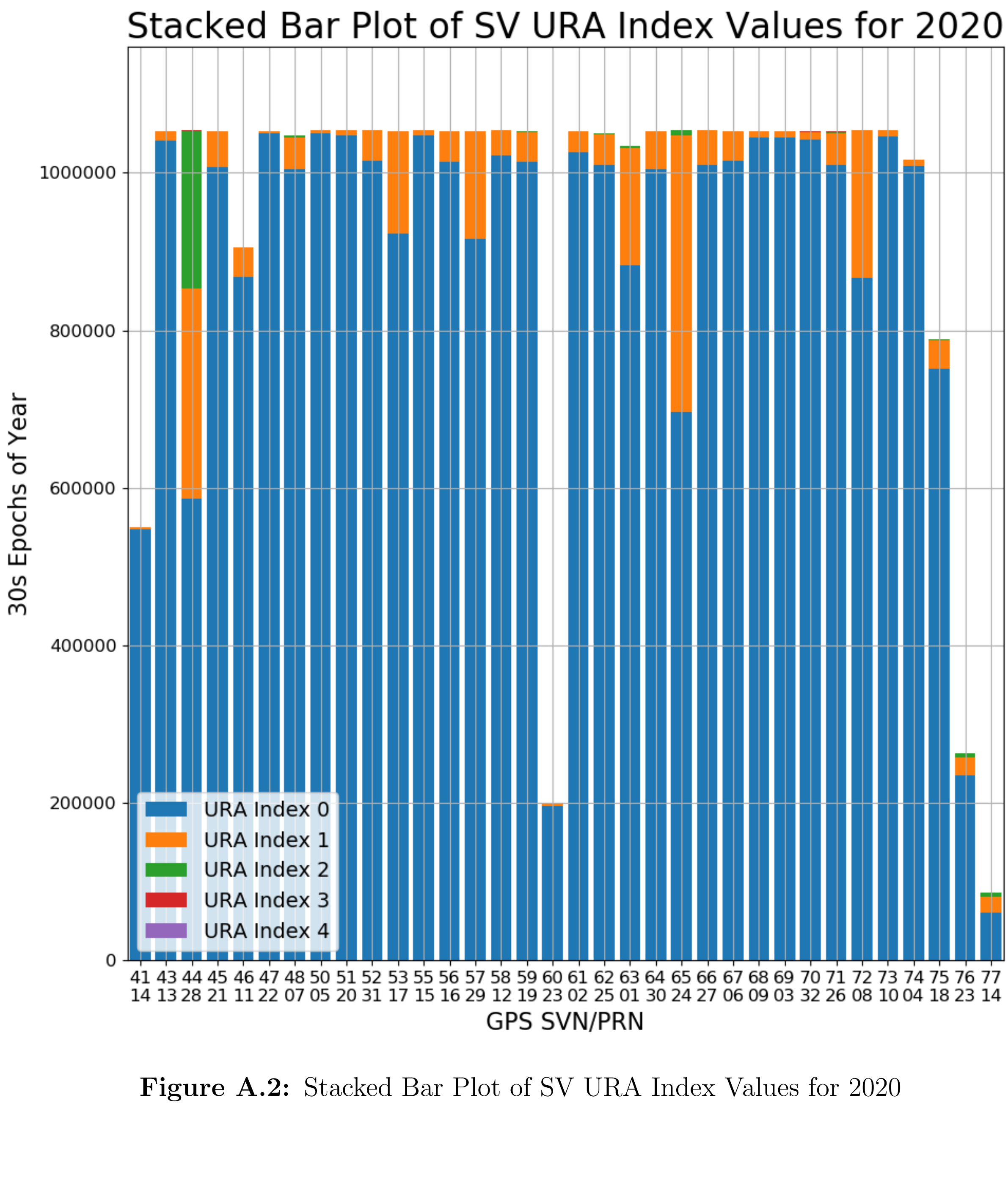


Figure A.2: Stacked Bar Plot of SV URA Index Values for 2020

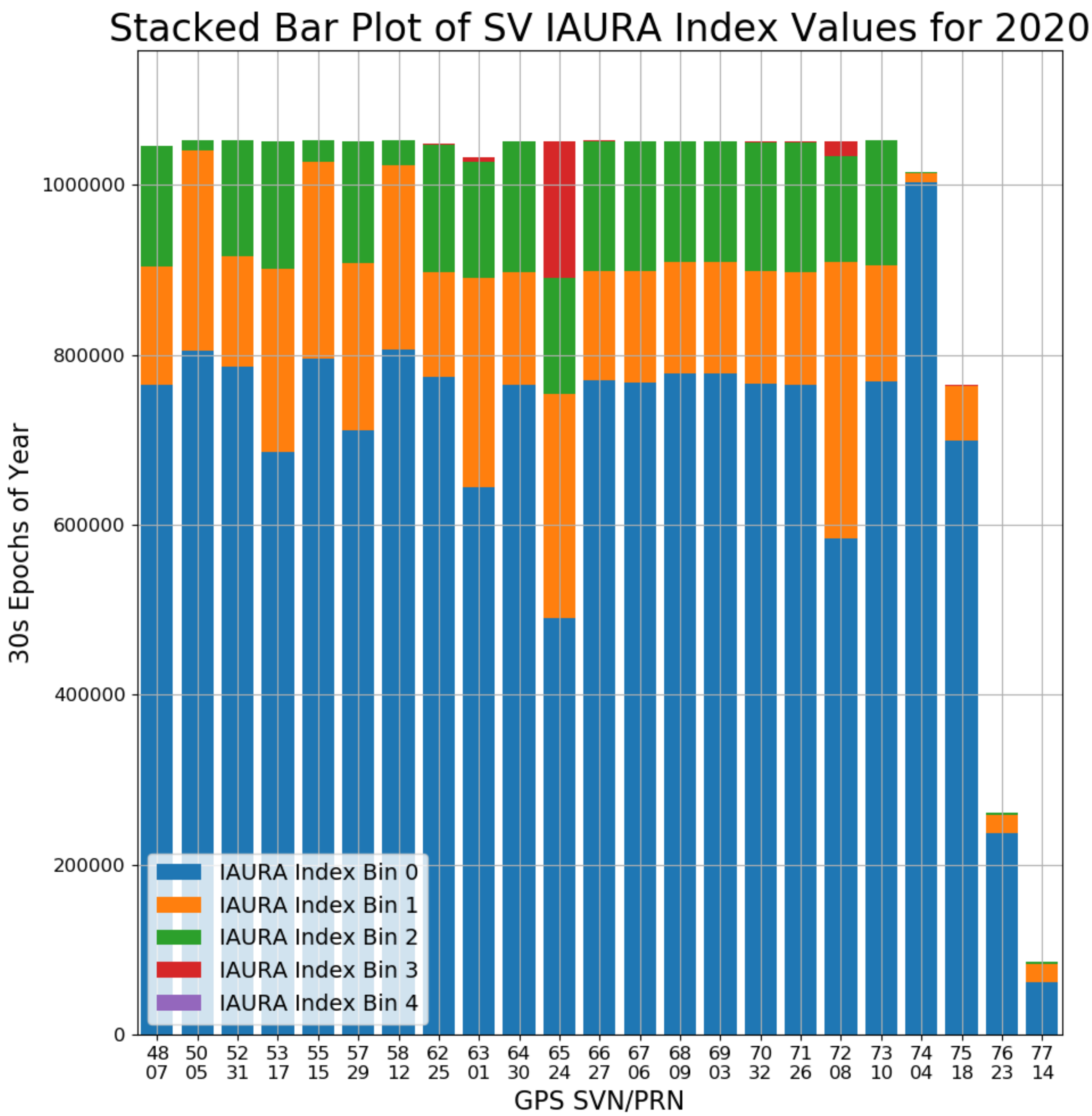


Figure A.3: Stacked Bar Plot of Binned SV IAURA Index Values for 2020

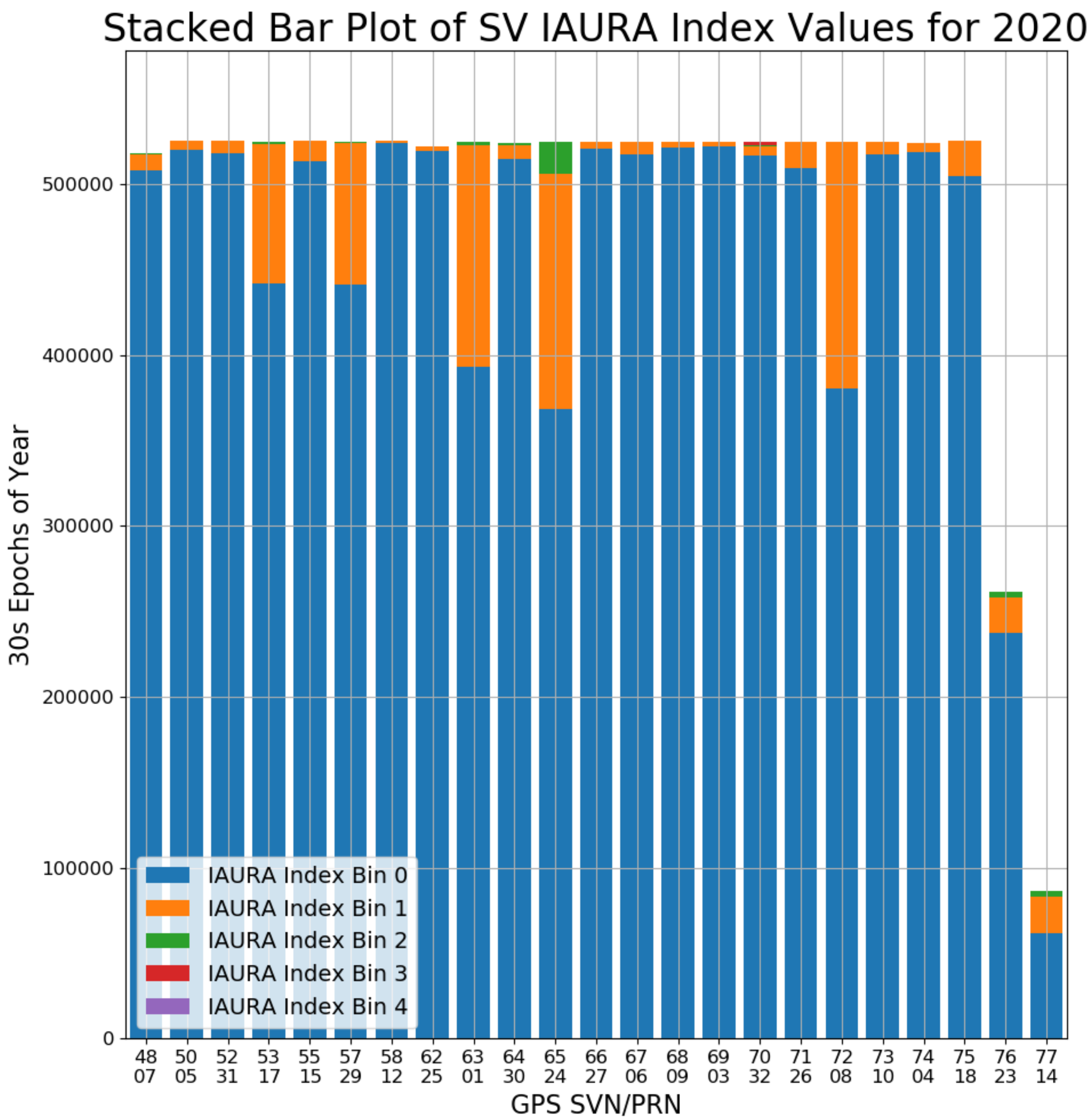


Figure A.4: Stacked Bar Plot of Binned SV IAURA Index Values for Second Half of 2020

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 SPSPS20 for the URE metrics. To determine if any SV operated in other than Normal Operations at any time in 2020, the broadcast ephemerides were examined to determine if any contained fit interval flags 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 25 examples of extended operations for satellites set healthy. The examples were distributed across 42 days. The average time of an occurrence was 38 minutes. The minimum duration was 30 seconds and the maximum duration was 4 hours 56 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 SPSPS20 would suggest that they be removed. However, the SVs involved were still set healthy and (presumably) being used by user equipment, it is appropriate to include these results to reflect performance seen by the users.

Examination of the ephemerides from past years reveals that 2020 is not an anomaly. Such periods have been found in all years checked (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	16	0
45	21	1	0	4	0
46	11	1	0	0	0
47	22	1	0	31	0
50	05	2	0	34	0
52	31	1	0	17	0
56	16	2	0	81	0
57	29	2	0	76	0
58	12	3	0	104	0
60	23	1	0	29	0
64	30	1	0	296	0
65	24	2	0	43	0
66	27	2	0	7	0
67	06	1	0	97	0
68	09	1	0	51	0
69	03	2	0	62	0
Totals		25	0	948	0

A.4.1 Long-Term Extended Operations Test for SVN 76/PRN 23

From 31 July 0330Z through 30 September 2315Z the third GPS III SV (SVN 76/PRN 23) was allowed to operate without an upload. The SV was transmitting an unhealthy indication throughout the period. Even though the SV was unhealthy and not yet operational, the URE values were computed throughout the period. This provides a rare example of how operation during long-term extended operations might appear.

Figure A.5 is a time-history of the SIS RMS URE on a logarithmic scale throughout the test period. The assertion is that the 95$^{\text{th}}$% Global Statistic will be less than 388 m at 14 days after the last upload. The 388 m threshold is represented by the red horizontal line in Figure A.5. The 14 day mark occurred at 14 August 0330Z. Clearly, the metric is below 388 m at 14 days. The discontinuity on 28 August is due to the transition from data sets with a 12 hour fit interval to data sets with a 24 hour fit interval.

The reader is cautioned against extrapolating these results to the constellation as a whole. The following points illustrate two reasons for this caution.

- Recall this period occurred shortly after the launch of the SV. The operators had a short time in which to determine the SV clock tuning prior to the beginning of the test. A better-characterized SV clock would likely yield better results.
- The GPS III SVs receive a state vector upload which is propagated forward on board the SV. This is in contrast to all earlier SVs, for which navigation messages for the entire period are generated by the control segment and uploaded as part of the regular SV upload. That means this particular test reflects the propagation quality of the GPS III SV, but it does not represent what the control segment propagator might have accomplished for an earlier GPS SV block.

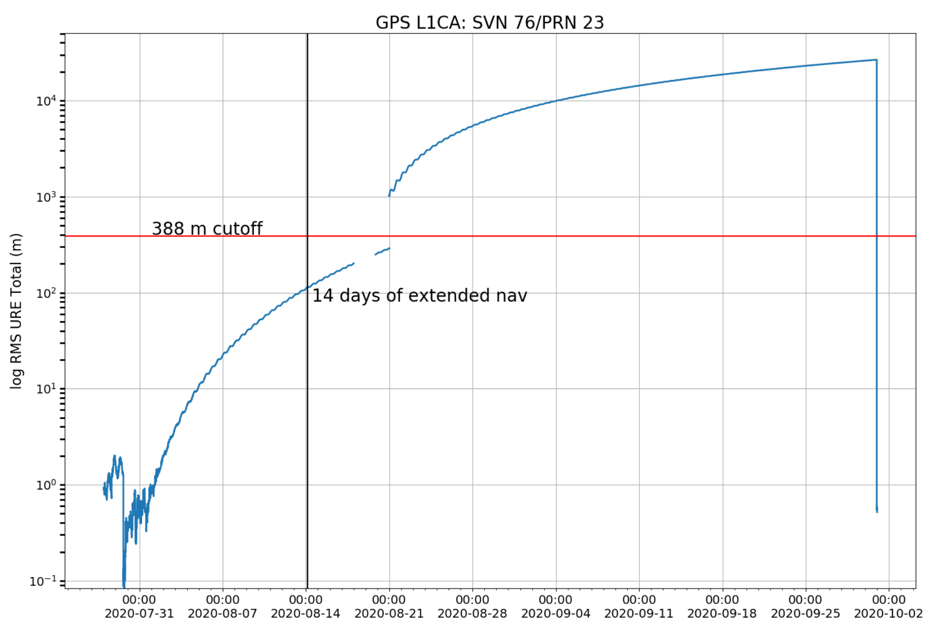


Figure A.5: L1 C/A SIS RMS URE for SVN 76/PRN 23 during Extended Operations

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 - 3.10 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 same set of 30 s Instantaneous RMS SIS URE values used in Section 3.2.1. 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. Since GPS SVs are typically uploaded daily, bins beyond 24 hours of 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. 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.

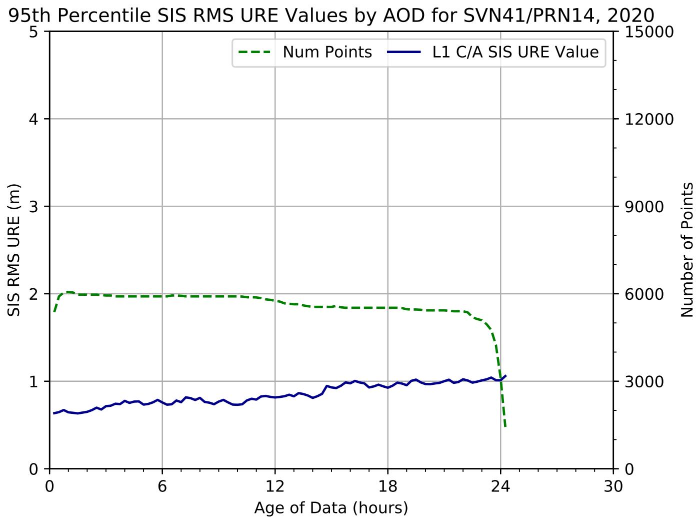
The count of points in each bin as a function of AOD for L1 C/A are plotted. This is representative of the curves for other signal combinations for a given SV as the unhealthy periods for all signals for a given SV are very nearly coordinated. Note that for most SVs, the counts curve has a well-defined horizontal plateau that begins near zero AOD, continues for roughly 24 hours, and then drops quickly toward zero. The location of the right-hand drop of the counts curve toward zero provides an estimate of the typical upload period for the SV. In cases where the SV is uploaded more frequently, the shape of the counts curve will vary reflecting that difference.

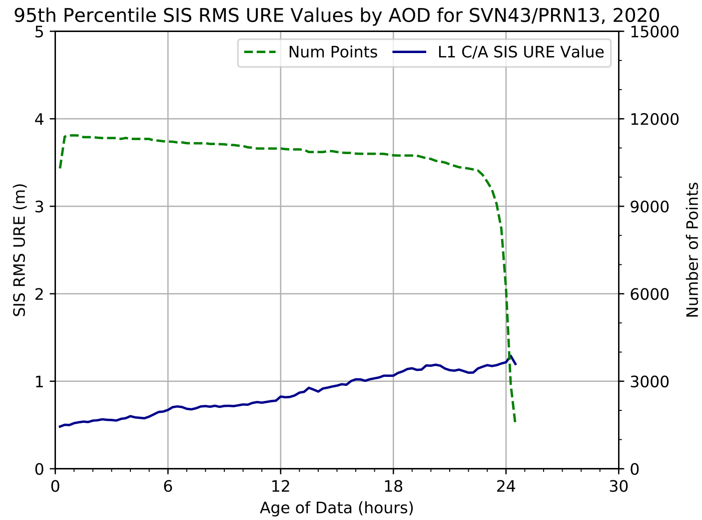
A.5.1 SPS Results

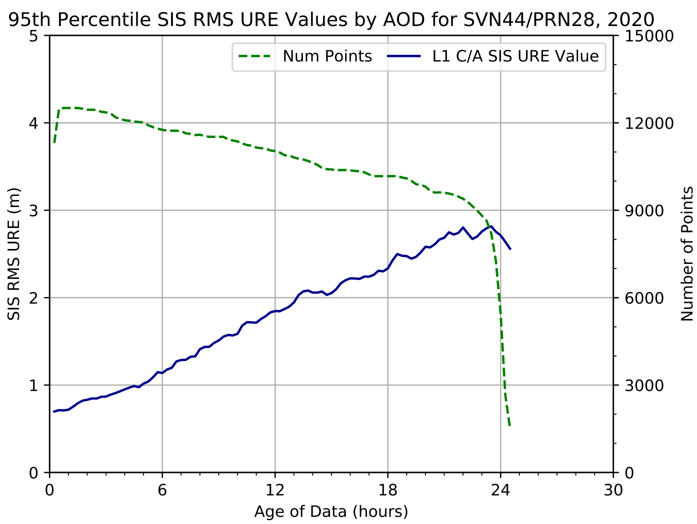
The figures on the following pages each show up to four curves:

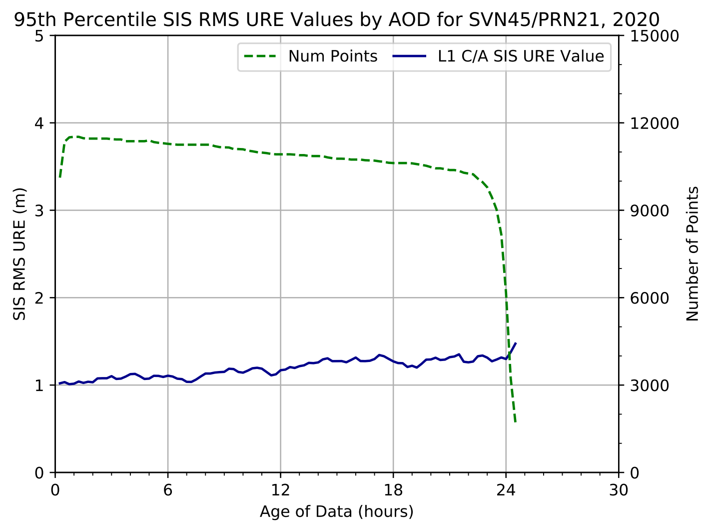
- Blue: 95th percentile SIS RMS URE vs. AOD for L1 C/A
- Magenta: 95th percentile SIS RMS URE vs. AOD for L1 C/A + L2C
- Cyan: 95th percentile SIS RMS URE vs. AOD for L1 C/A + L5Q
- Green: count of points in each bin as a function of AOD for L1 C/A

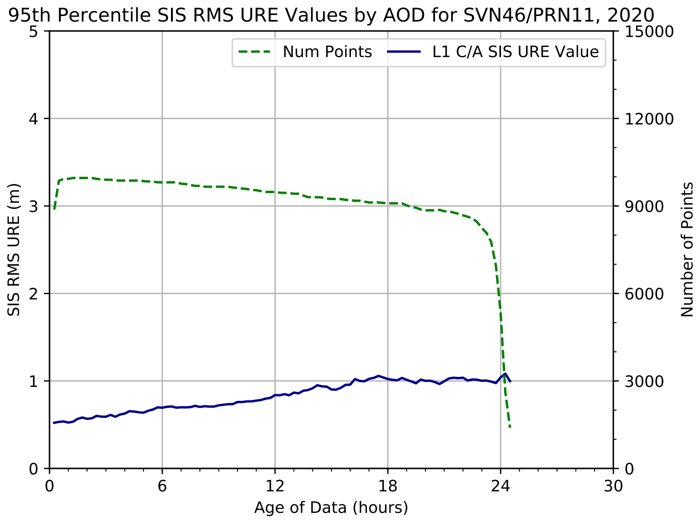
A.5.1.1 Block IIR SVs

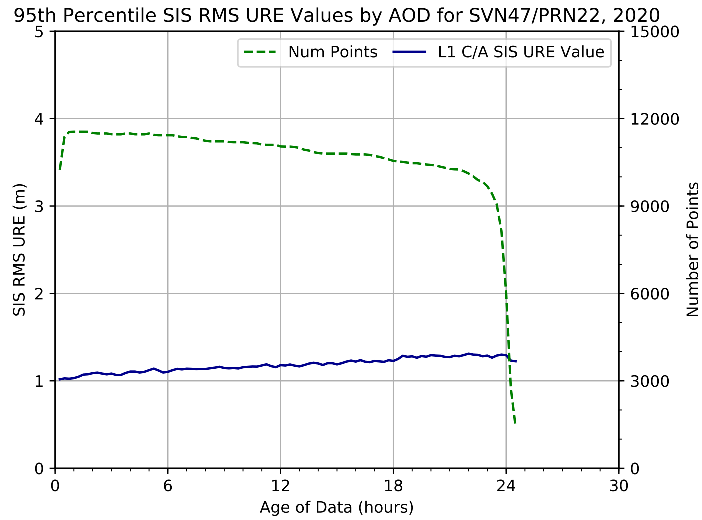


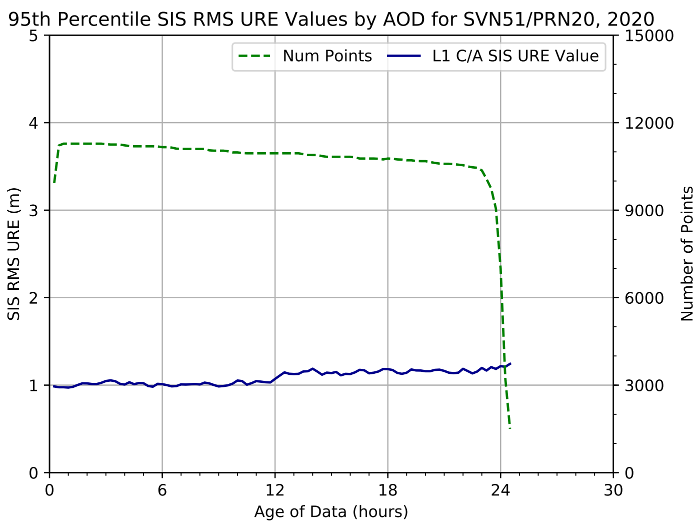


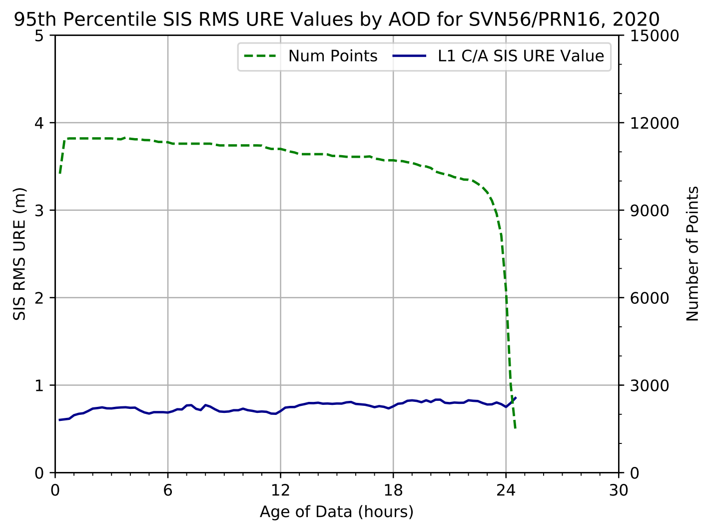


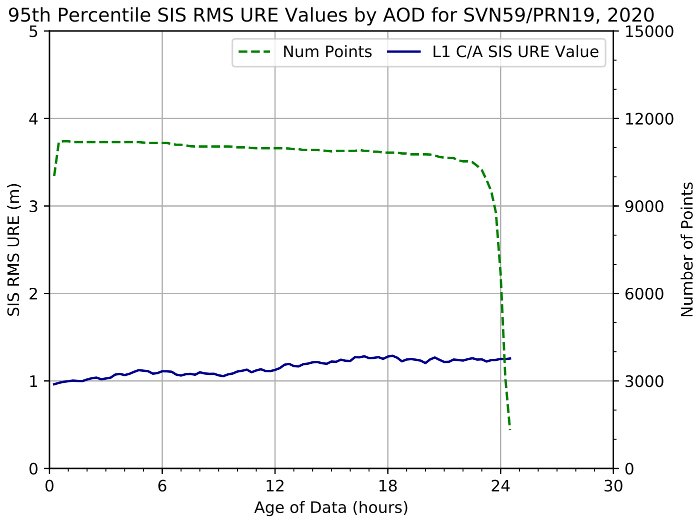


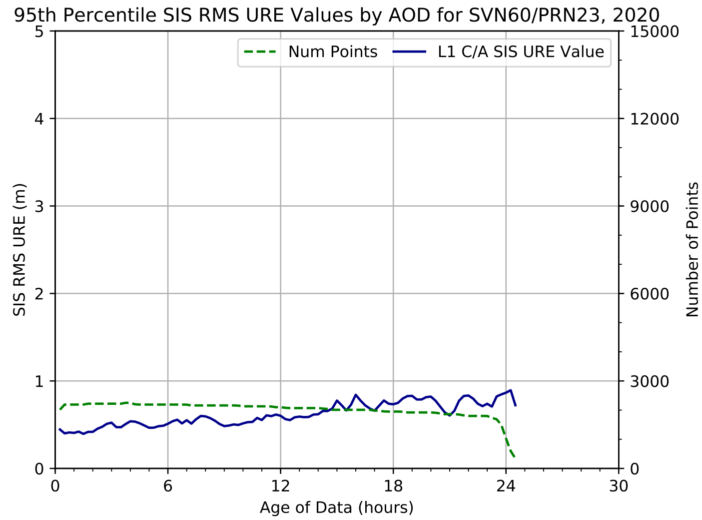

95th Percentile SIS RMS URE Values by AOD for SVN46/PRN11, 2020
Num Points
L1 C/A SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)

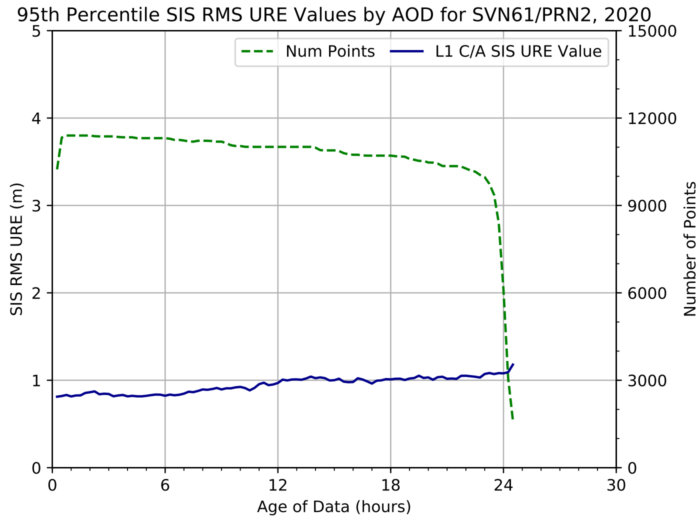

95th Percentile SIS RMS URE Values by AOD for SVN47/PRN22, 2020
Num Points
L1 C/A SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)


95th Percentile SIS RMS URE Values by AOD for SVN51/PRN20, 2020
Num Points
L1 C/A SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)

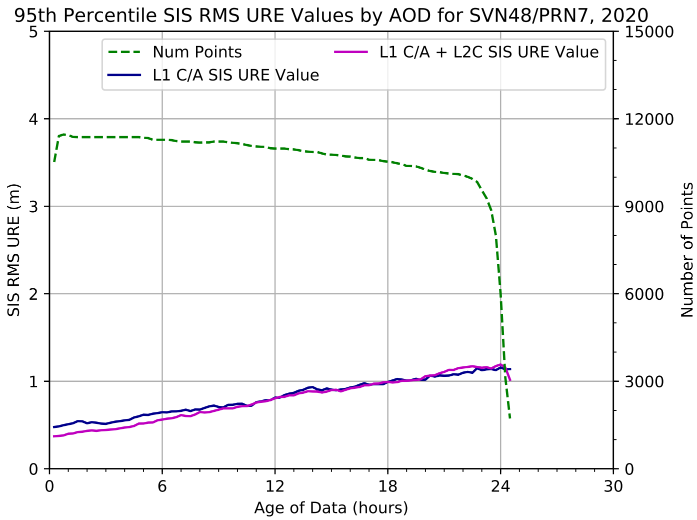

95th Percentile SIS RMS URE Values by AOD for SVN56/PRN16, 2020
Num Points
L1 C/A SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)

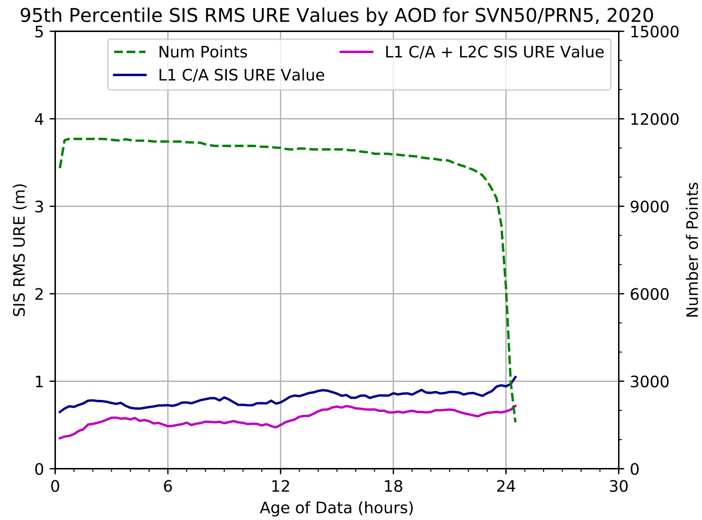

95th Percentile SIS RMS URE Values by AOD for SVN59/PRN19, 2020
Num Points
L1 C/A SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0
1
2
3
4
5
0
6
12
18
24
30
0
3000
6000
9000
12000
15000

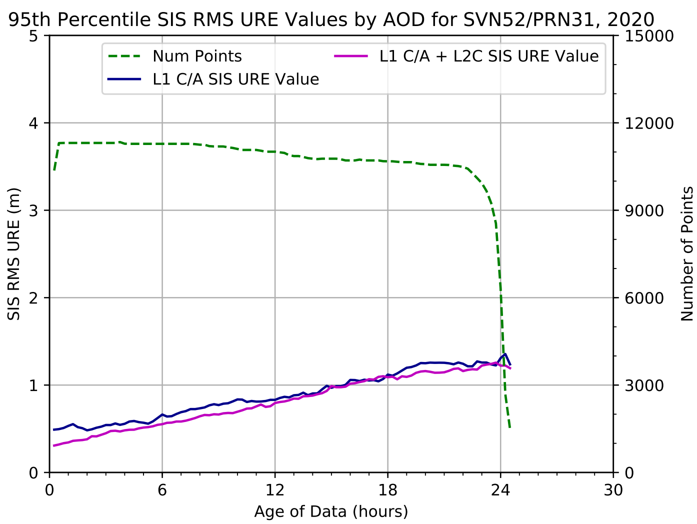

95th Percentile SIS RMS URE Values by AOD for SVN60/PRN23, 2020
Num Points
L1 C/A SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0
1
2
3
4
5
0
6
12
18
24
30
0
3000
6000
9000
12000
15000

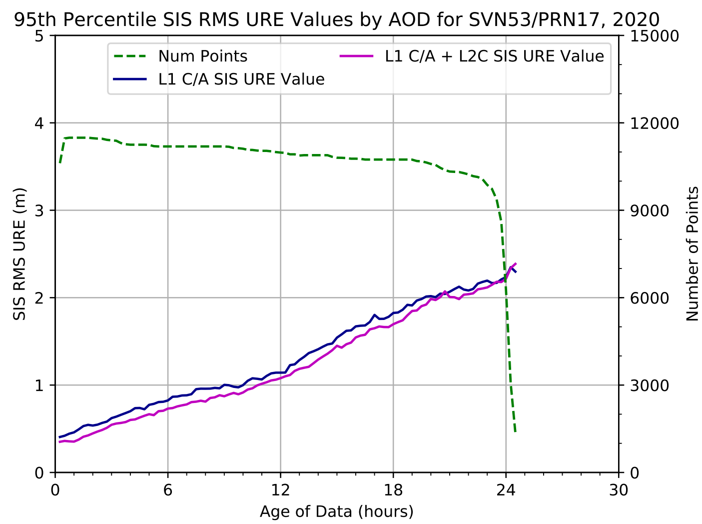

95th Percentile SIS RMS URE Values by AOD for SVN61/PRN2, 2020
Num Points
L1 C/A SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0
1
2
3
4
5
0
6
12
18
24
30
0
3000
6000
9000
12000
15000

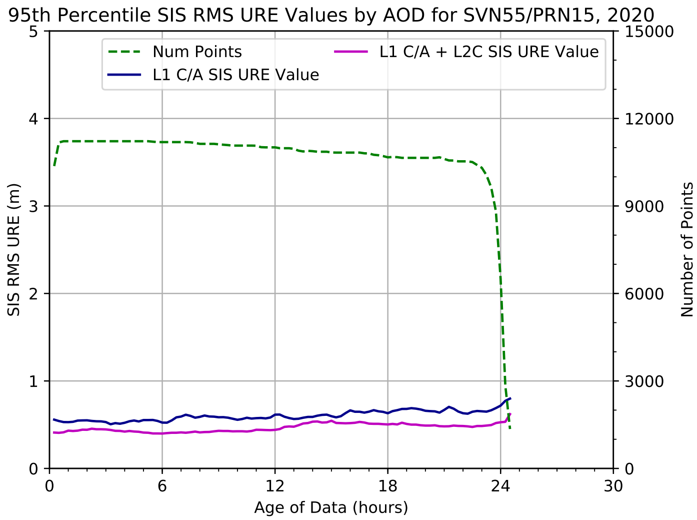
A.5.1.2 Block IIR-M SVs

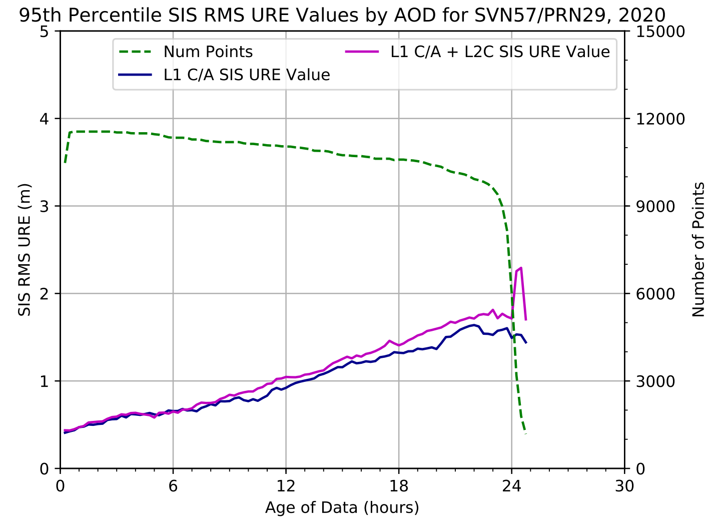


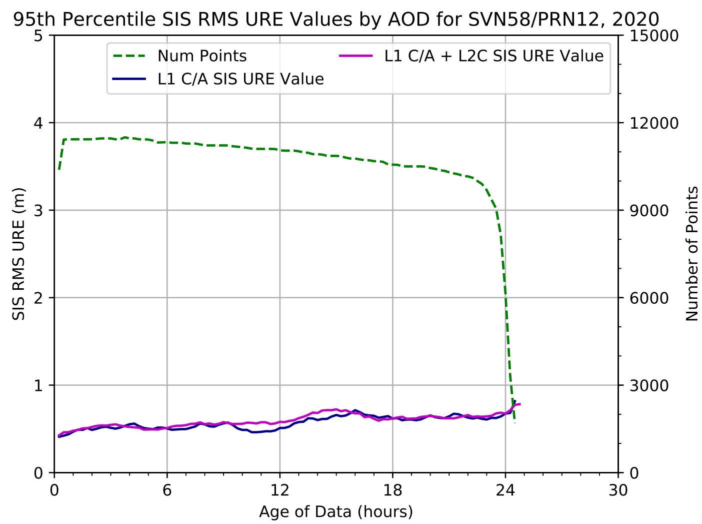




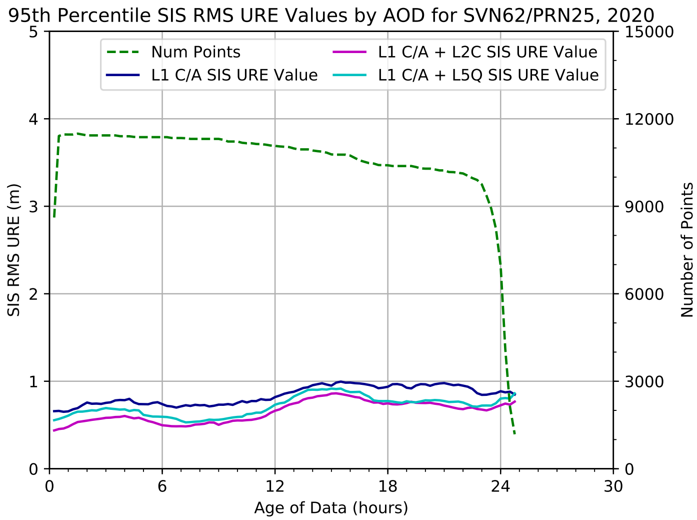


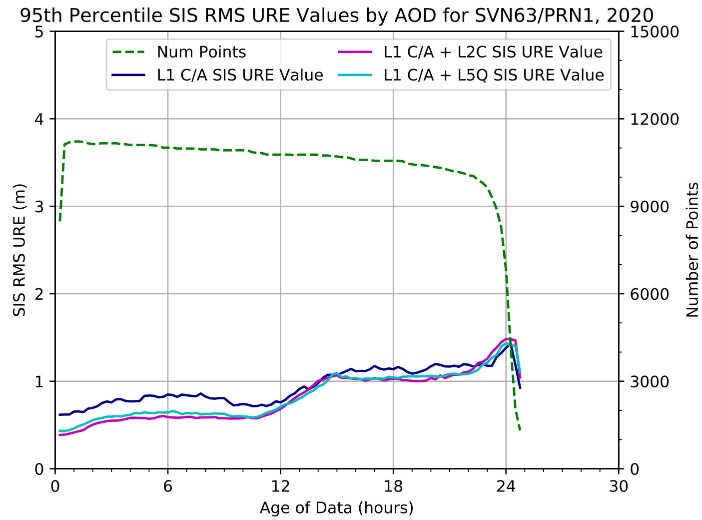

95th Percentile SIS RMS URE Values by AOD for SVN55/PRN15, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0
1
2
3
4
5
6
12
18
24
30
3000
6000
9000
12000
15000

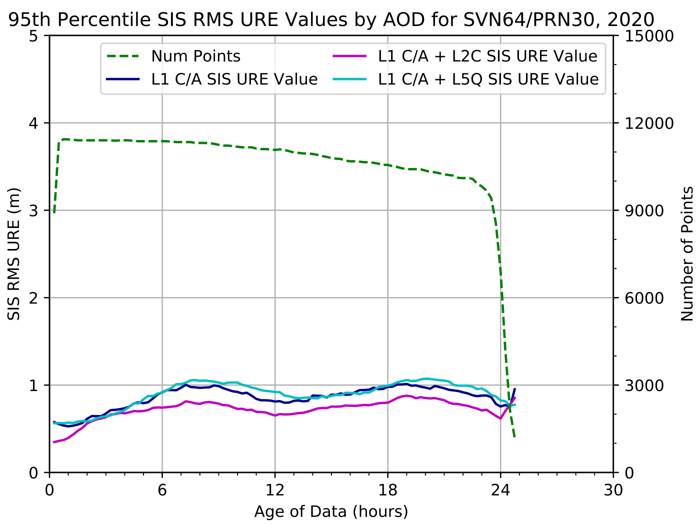

95th Percentile SIS RMS URE Values by AOD for SVN57/PRN29, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0
1
2
3
4
5
6
12
18
24
30
3000
6000
9000
12000
15000

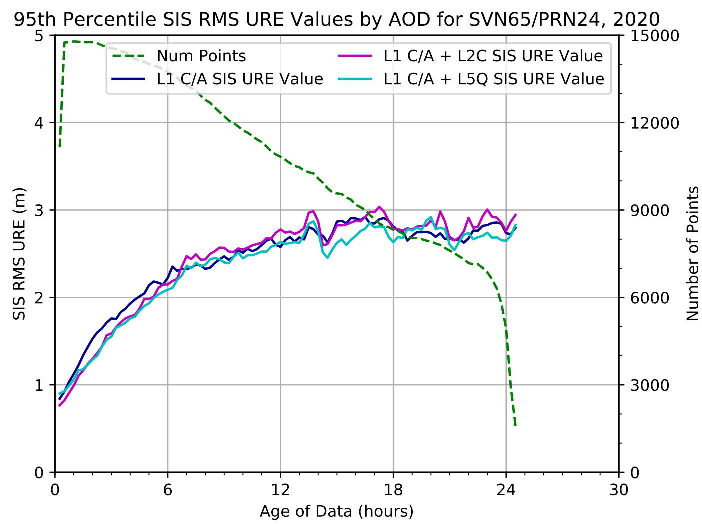

95th Percentile SIS RMS URE Values by AOD for SVN58/PRN12, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0
1
2
3
4
5
6
12
18
24
30
3000
6000
9000
12000
15000

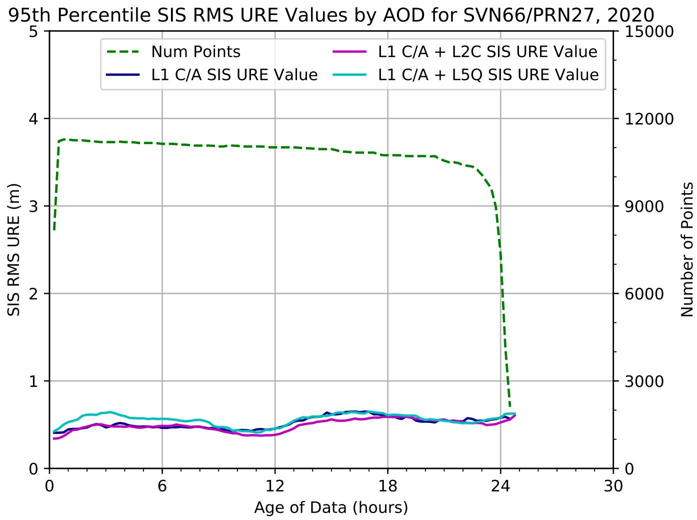
A.5.1.3 Block IIF SVs

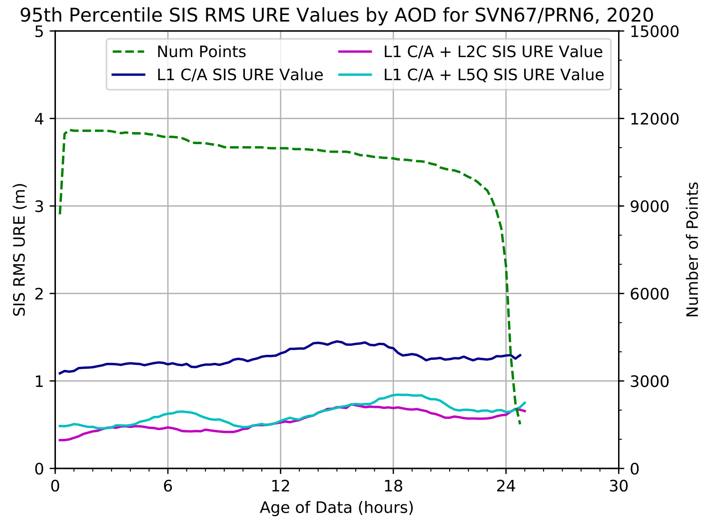


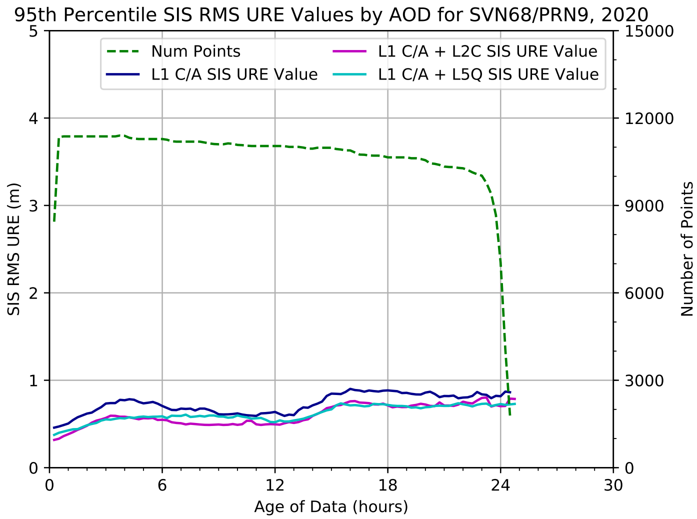


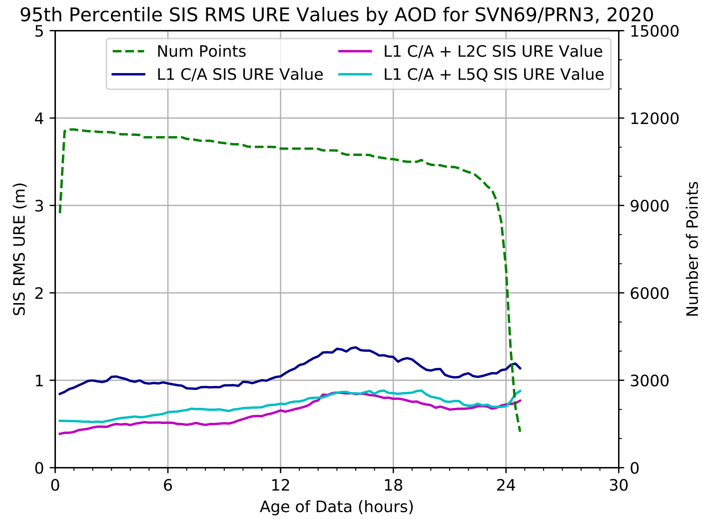


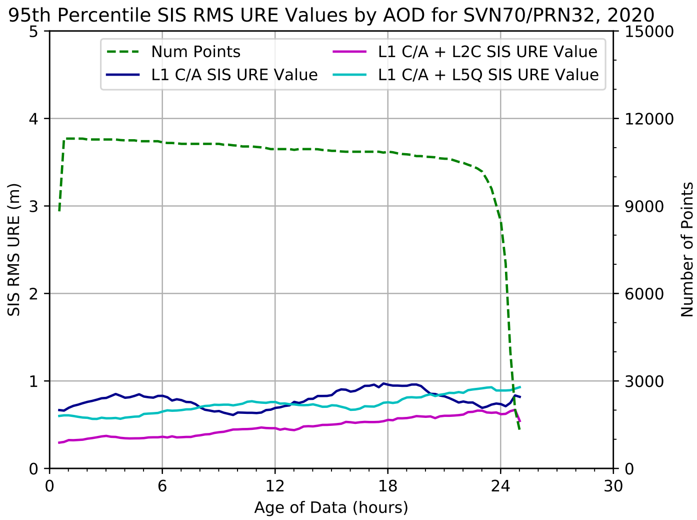


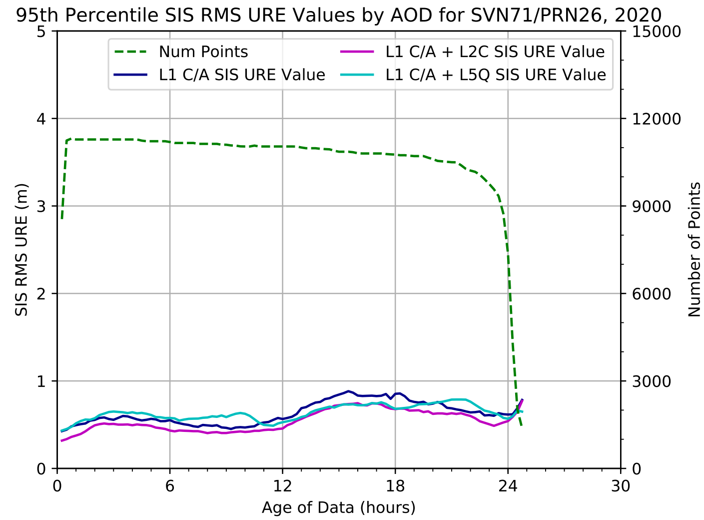

95th Percentile SIS RMS URE Values by AOD for SVN66/PRN27, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
L1 C/A + L5Q SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0 1 2 3 4 5
0 3000 6000 9000 12000 15000
0 6 12 18 24 30

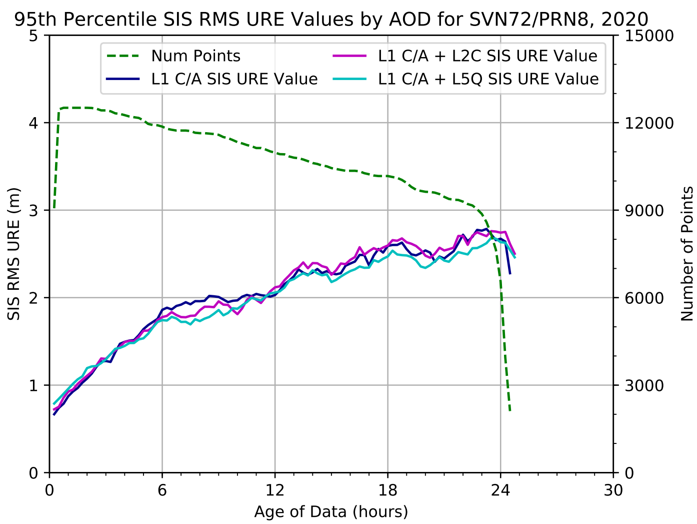

95th Percentile SIS RMS URE Values by AOD for SVN67/PRN6, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
L1 C/A + L5Q SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0 1 2 3 4 5
0 3000 6000 9000 12000 15000
0 6 12 18 24 30

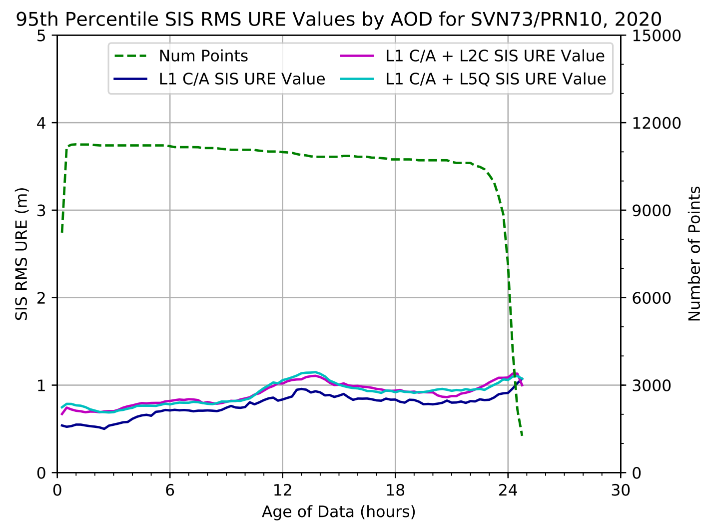

95th Percentile SIS RMS URE Values by AOD for SVN68/PRN9, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
L1 C/A + L5Q SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0 1 2 3 4 5
0 3000 6000 9000 12000 15000
0 6 12 18 24 30


95th Percentile SIS RMS URE Values by AOD for SVN69/PRN3, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
L1 C/A + L5Q SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0 1 2 3 4 5
0 3000 6000 9000 12000 15000
0 6 12 18 24 30

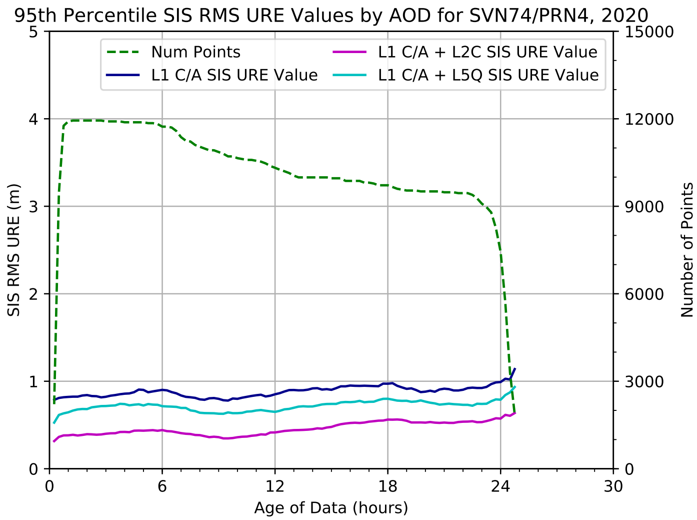

95th Percentile SIS RMS URE Values by AOD for SVN70/PRN32, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
L1 C/A + L5Q SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0 1 2 3 4 5
0 3000 6000 9000 12000 15000
0 6 12 18 24 30

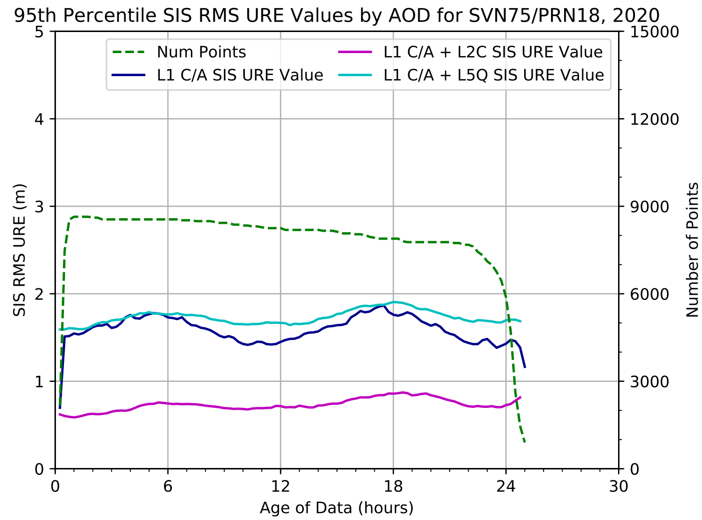

95th Percentile SIS RMS URE Values by AOD for SVN71/PRN26, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
L1 C/A + L5Q SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0 1 2 3 4 5
0 3000 6000 9000 12000 15000
0 6 12 18 24 30

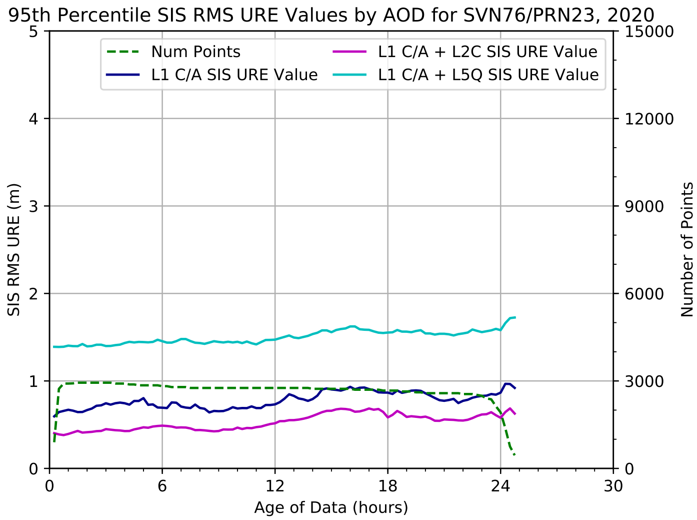

95th Percentile SIS RMS URE Values by AOD for SVN72/PRN8, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
L1 C/A + L5Q SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0 1 2 3 4 5
0 3000 6000 9000 12000 15000
0 6 12 18 24 30

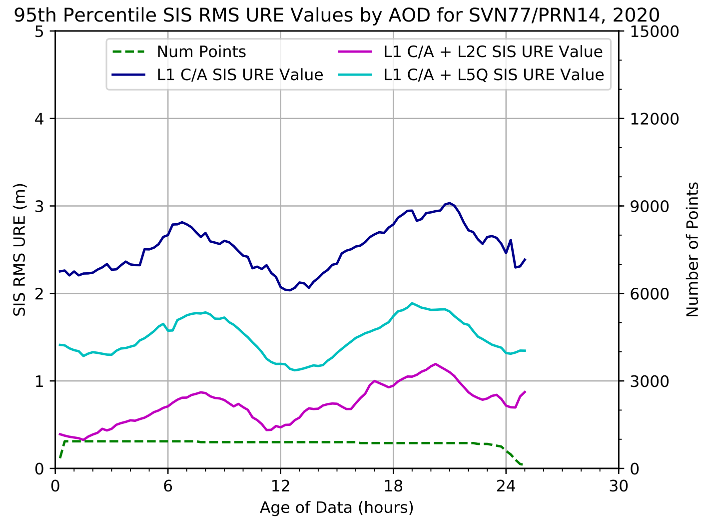

95th Percentile SIS RMS URE Values by AOD for SVN73/PRN10, 2020
Num Points
L1 C/A SIS URE Value
L1 C/A + L2C SIS URE Value
L1 C/A + L5Q SIS URE Value
SIS RMS URE (m)
Number of Points
Age of Data (hours)
0 1 2 3 4 5
0 3000 6000 9000 12000 15000
0 6 12 18 24 30

A.5.1.4 GPS III SVs









Appendix B

Supporting Data

This chapter includes supporting data for the analysis.

B.1 PRN to SVN Mapping for 2020

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. Keeping track of this relationship has become more challenging over the past few years as 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 2020. SVNs on the right vertical axis appear in the order in which they were assigned the PRN values in 2020. Colored bars indicate the range of time each relationship was in effect. Start and end times of relationships are indicated by the dates at the top of the chart.

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 SOPS.

B.2 NANU Activity in 2020

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 2020. Blue bars represent scheduled outages and red bars represent unscheduled outages. Gray bars represent SVs that were decommissioned in 2020. Light green bars represent SVs after launch prior to a NANU declaring initial usability. Teal bars indicate scheduled outages with notice of less than 48 hours. There was one such event in 2020. 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.

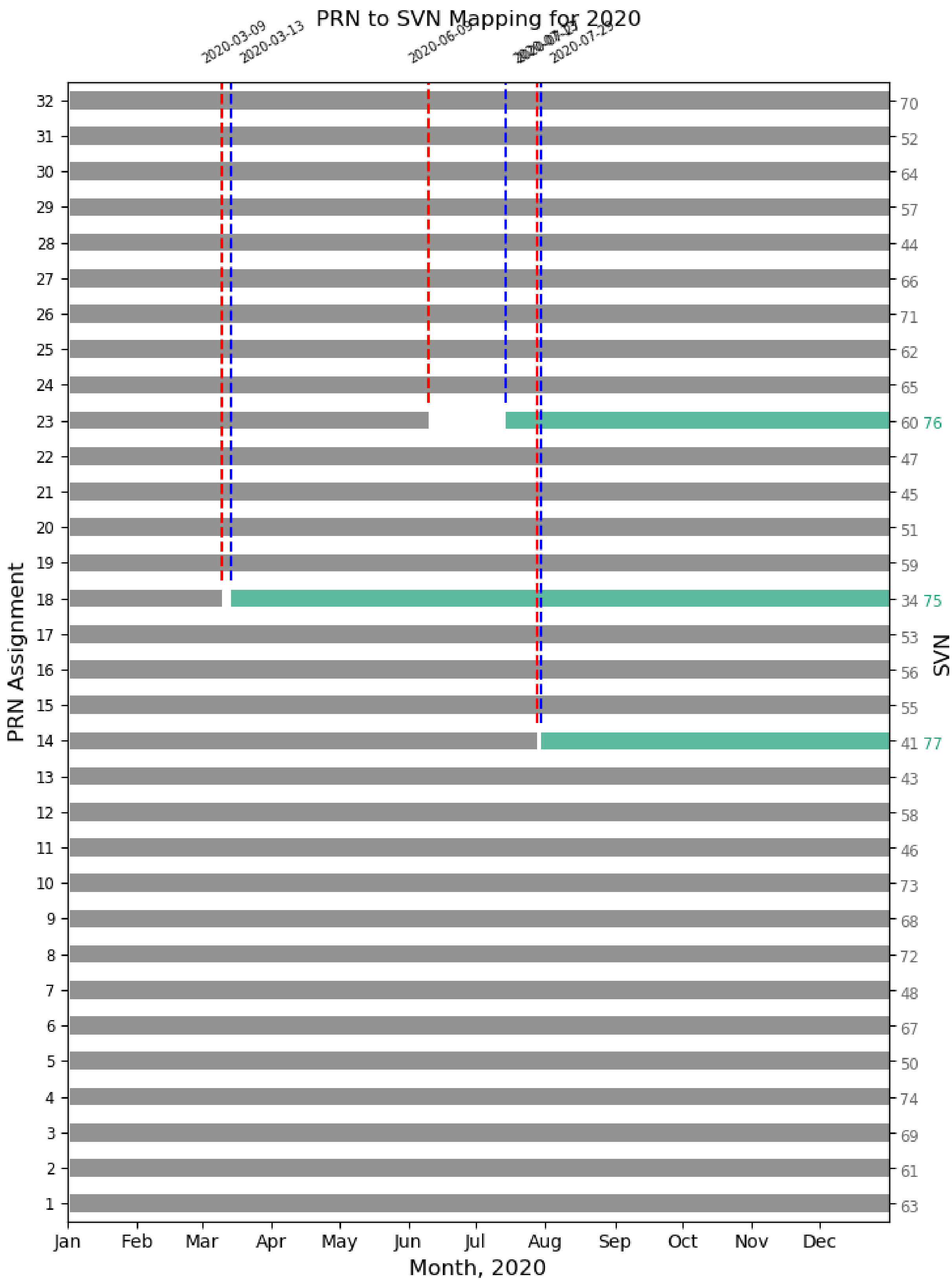


Figure B.1: PRN to SVN Mapping for 2020

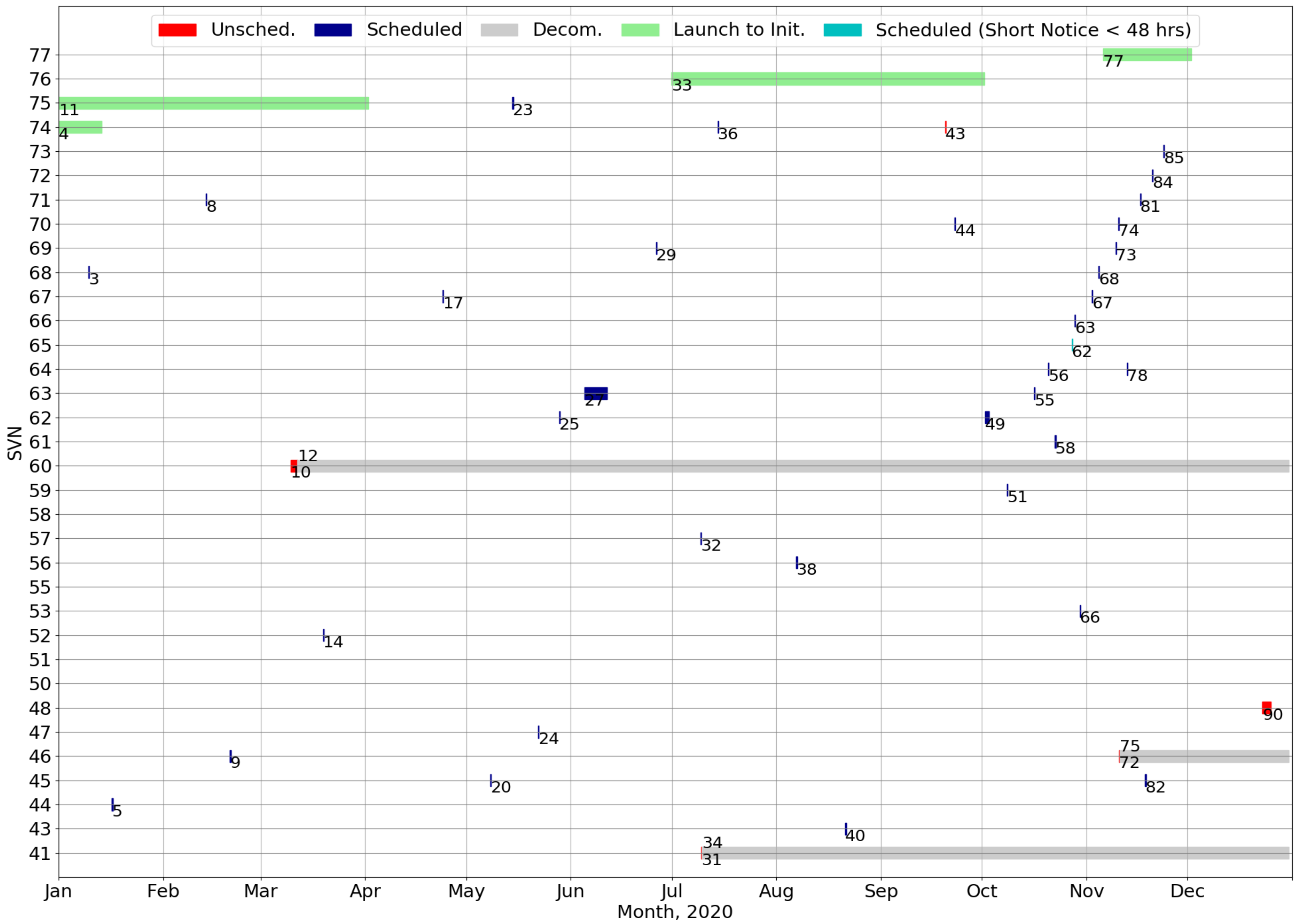


Figure B.2: Plot of NANU Activity for 2020

B.3 SVN to Plane-Slot Mapping for 2020

Several assertions are related to the performance of the constellation as defined by the plane-slot arrangement specified in the performance standard. The standard defines six planes lettered A-F. Each plane contains four slots numbered 1-4. For each plane, one slot in each plane may be expanded into a pair of locations designated by the addition of the letters F (fore) or A (aft). The possible plane-slot designators appear on the vertical axis of Figure B.3. Evalution of these assertions requires information on the plane-slot occupancy during the year.

The constellation definition located in Section 3.2 of the SPSPS20 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 by the Groundtrack Equatorial Crossing (GEC) value (also known as the Geographic Longitude of the Ascending Node (GLAN) value). In the real world, discrepancies in orbit insertion lead to a situation in which some SVs are less well-positioned than others. The operators manage the SV locations within the constellation in order to achieve the desired coverage (DOP) as documented in Section 3.6. In some cases, this means assigning plane-slot identifiers to SVs that are fulfilling the responsibility of a particular plane-slot but may not be strictly within the slot as defined by GEC (GLAN). This makes independent verification of plane-slot assignments a challenge.

Information on plane-slot assignment appears in the operational advisory (OA) provided by 2 SOPS to the USCG Navigation Center, defined in ICD-GPS-240. However, the format does not permit clarity for expanded slots: there is no provision for “fore/aft” designation. Also, designations for plane/slot contain numbers greater than the number of designated slots. The operators define these “slots of convenience” without fixed meaning for constellation position. As a result, OA interpretation can be challenging. During 2020, 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.

For the past several years, the plane-slot assignments have been provided to ARL:UT by The Aerospace Corporation analysts supporting 2 SOPS. The assignments are provided as a set of daily plane-slot relationships. This information source is not publicly available.

Both of these sources are limited in that only a single satellite may be designated as being present in a slot at a given moment. As satellites are moved within the constellation, there exist occasional 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.

Figure B.3 provides a graphical illustration of the plane-slot relationships throughout 2020. The contents of Figure B.3 are primarily drawn from the information provided by The Aerospace Corporation and cross-checked against the operational advisories. 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.

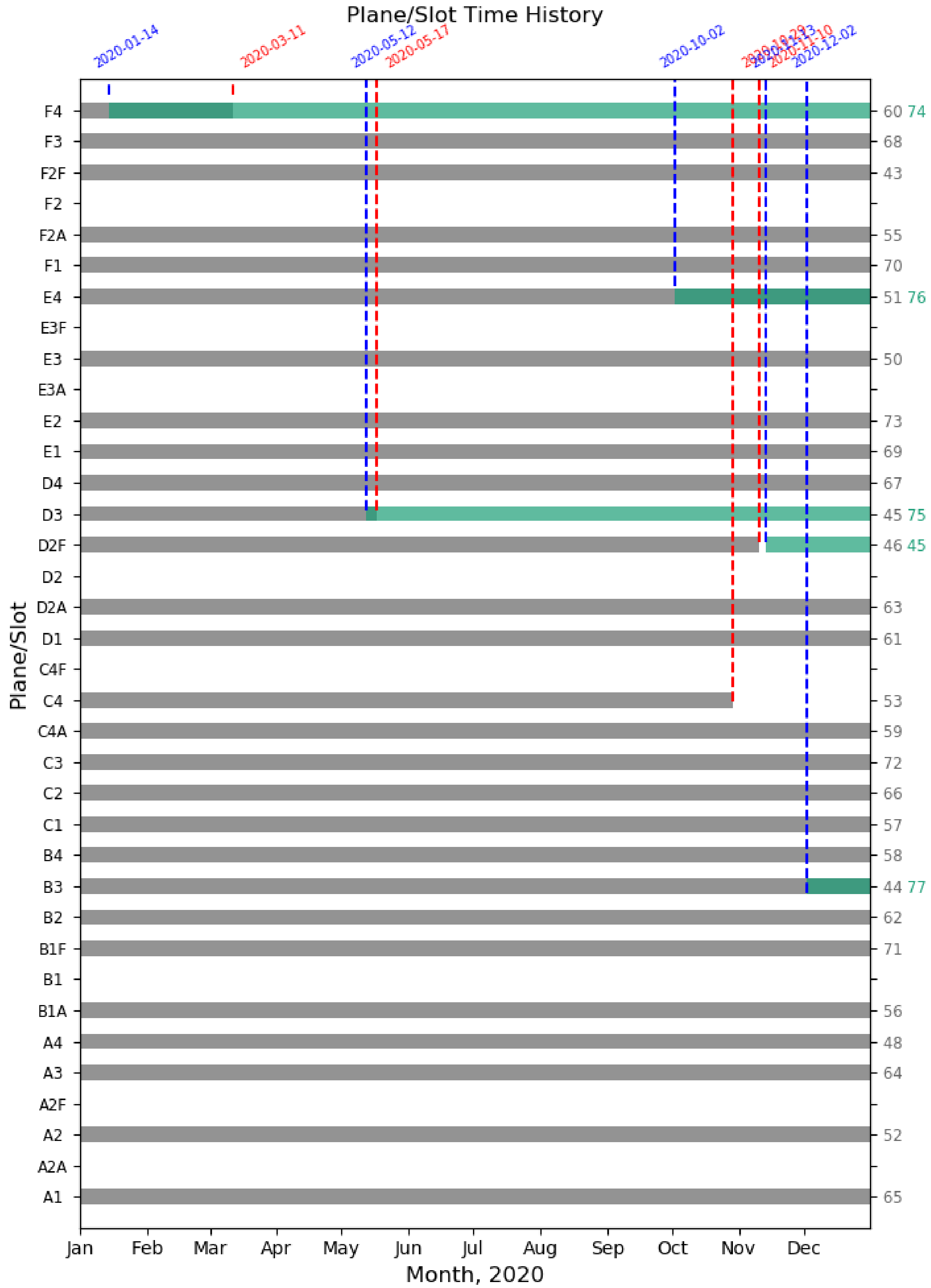


Figure B.3: Time History of Satellite Plane-Slots for 2020

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, and the means by which AOD is computed.

C.1 Signals Used

Several dual-frequency and triple-frequency signal combinations are listed in SPSPS20 as shown 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. 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 Component Combinations Covered by SPSPS20

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

The selected signal combinations 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: Rationale for Selection of Signal Combinations

Signal Combination	**Navigation Message**	**Rationale**
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 a large number of 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 BCP against the TCP. This is a useful approach, but one that has specific limitations, the most significant being that the TCP 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 TCP carries an implicit network dependency based on the set of ground stations used to derive the precise orbits from which the TCP 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 URE numbers.

Throughout this section, there are references to the "Instantaneous RMS SIS 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 RMS SIS 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 SPSPS20 Section A.4.11, and the relevant equation is presented in Appendix C.2.4 of this report.

Appendix A.4.11 of the SPSPS20 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 for a time period.

When the BCP and TCP 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 (±) 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 Truth

The BCP values used in this report are derived from multiple GPS navigation messages. Specifically, see Table C.2.

The clock and position values from LNAV, CNAV-L2C, and CNAV-L5I are typically the same (discounting very small differences in dataset cutover time). However, using all three messages verifies that this assumption of commonality is correct. The CNAV-L2C and CNAV-L5I messages are also needed for intersignal correction (ISC) values that are required for the evaluation of L1 C/A + L2C and L1 C/A + L5Q URE values. This will be described in Appendix C.2.2.

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 provides 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 TCP 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 [15]. 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 TCP 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 is not necessary to solve for a system time bias between the BCP and the TCP.

The NGA product is published in tabular SP3 format, with positions and clocks provided at a 5 min cadence. For 30 s cadence analysis, Lagrange interpolation is sufficient for calculating SV positions, using the five points prior to and after the desired epoch; linear interpolation is sufficient for 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 fact that the effective phase center of each signal combination differs from that of the primary signal combination represented in the broadcast orbit. The differences cause range errors that appear as clock errors. These differences are quantified in the broadcast intersignal correction (ISC) values and equations provided in the interface specifications 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. 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 URE process may account for ISC errors in the following manner:

- 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 truth.
- Continue with the regular URE evaluation process using the adjusted clock errors.

Note the reliance on ISC truth 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 likely not the case, but it is assumed common errors will be removed from the process.

There are two organizations within the IGS that regularly evaluate the ISC values (described as differential code bias (DCB) values): DLR (Germany) and IGG CAS (China). For the remainder of this section, the DCB values produced by DLR will be considered. This choice is based on the fact that there is a paper describing how the DCB values are derived [16].

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 naming nomenclature. As expected, there are no DCBs based on Y-code, but only 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). This holds true for several cases.

- DLR produces both one-day and seven-day DCB values. These are published quarterly, usually one to two months after the end of a 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. As a result, there is no direct way to compare the GPS T_{GD} to anything derived from the DLR DCB. At best, T_{GD} values may be debiased and then the two data sets compared in order to determine the degree of uncertainty.

Some of these concerns can be addressed, though the manner in which we address them brings a different set of concerns.

- 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.

- We want to consistently use the NGA precise orbits when processing UREs for GPS as the NGA PE is directly tied to the GPS time scale using information provided to NGA by the operational system. For the primary signal combination, this allows us to skip the step in which a bias is removed from the UREs to account for differences in system time. However, if we solve for a system time bias for the signal combinations that are not the primary signal combination, this may be a step toward reducing the impact of the biases between the DCB values and the ISC values.

It is worth noting that we are not alone in addressing this concern. DLR itself uses a similar process to the one we propose in generating their URE estimates. This is addressed in Montenbruck (2018) [17]. 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	BE Correction to Clock Error	PE Correction to Clock Error
LNAV	L1 P(Y) + L2 P(Y)	0	0
	L1 P(Y)	T_{GD}	- γ_{L2L1} $DCB_{C1W\text{-}C2W}$
	L1 C/A	T_{GD}	- γ_{L2L1} $DCB_{C1W\text{-}C2W}$ + $DCB_{C1C\text{-}C2W}$
CNAV	L1 C/A	T_{GD} - ISC_{L1CA}	- γ_{L2L1} $DCB_{C1W\text{-}C2W}$ + $DCB_{C1C\text{-}C2W}$
	L1 C/A + L2C	T_{GD} - γ_{L1L2} ISC_{L1CA} + γ_{L2L1} ISC_{L2C}	γ_{L1L2} $DCB_{C1W\text{-}C2W}$ - γ_{L2L1} $DCB_{C2L\text{-}C2W}$
	L1 C/A + L5Q	T_{GD} - γ_{L1L5} ISC_{L1CA} + γ_{L5L1} ISC_{L5Q}	γ_{L1L5} $DCB_{C1W\text{-}C2W}$ - γ_{L1L5} $DCB_{C1C\text{-}C5Q}$

Where:

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

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 shown in the column "BE Correction to clock error" are the equations from the GPS interface specifications with the signs reversed.

The UREs contained in this report have been computed by applying the corrections in Table C.4 to the clock errors derived from the broadcast orbits and the precise orbits.

C.2.3 Definition of 95th Percentile Global Statistic

Where the SPSPS20 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 SPSPS20 Appendix A.4.11 extended over time as suggested by Note 1 in the same section. 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 577 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 2020 and all 577 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.

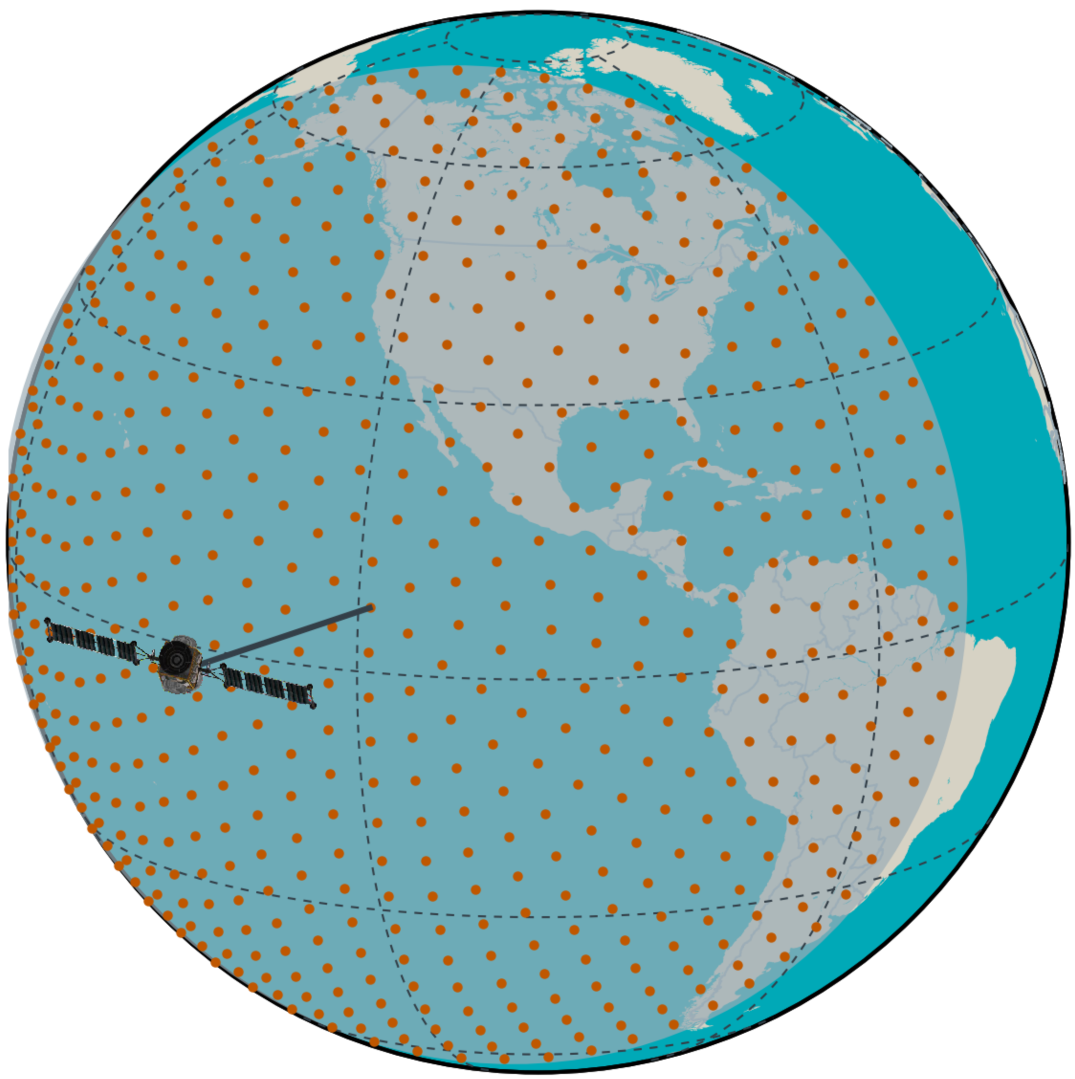


Figure C.1: Illustration of the 577 Point Grid

C.2.4 Definition of 95th Percentile Global Average

Where the PPSPS07 uses the term "95^{th}% 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 PPSPS07 Appendix A.4.11 is applied to obtain the Instantaneous SIS RMS URE at a series of time points, then
2. the 95^{th} percentile of the collection of Instantaneous SIS RMS URE values is selected as the statistic.

The first part of the process is illustrated in Figure C.2.

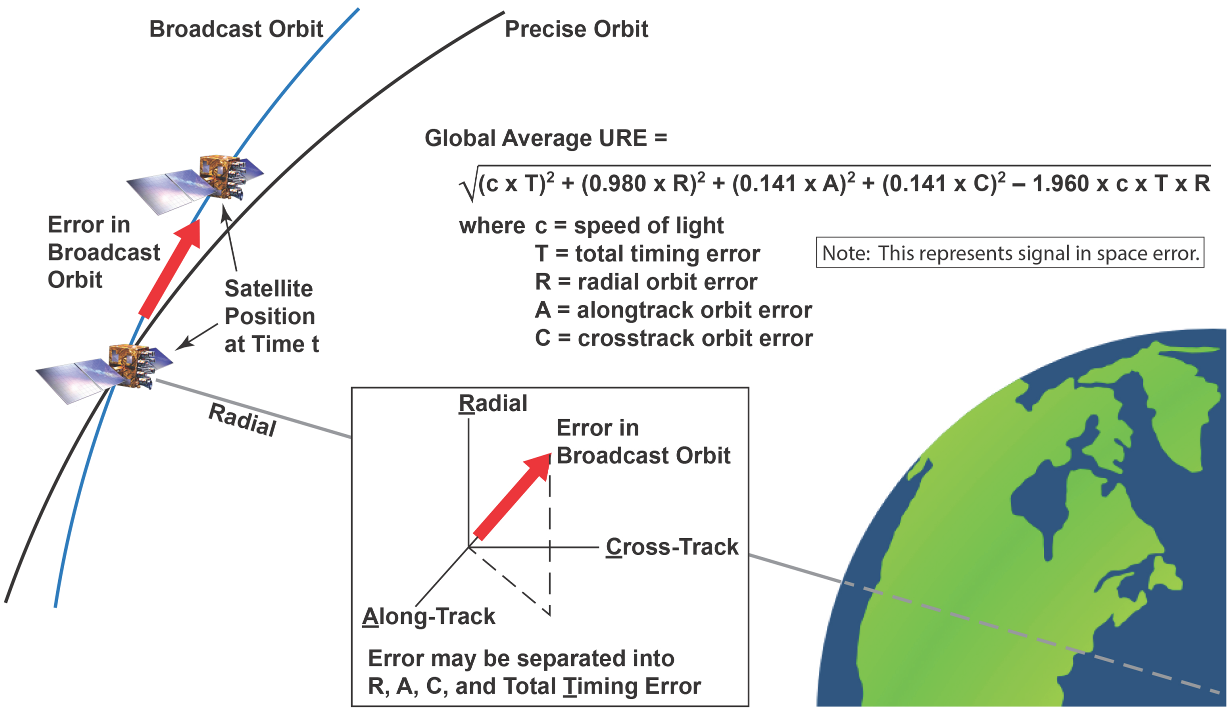


Figure C.2: Global Average URE as defined in PPS PS

The equation shown in Figure C.2 is Equation A-1 of PPSPS07 Section A.4.11. 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 RMS SIS URE values were generated at 30 s intervals for all of 2020. The URE was formed by differencing the BCP and TCP to obtain the radial, along-track, cross-track, and time errors at each epoch. These errors were used as inputs to the PPSPS07 Equation A-1.

After the Instantaneous RMS SIS 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 95$^{\text{th}}$ percentile values within a given month were identified for each SV. This is the basis for Table 3.1. The monthly grouping corresponds closely to the 30 day period suggested in Note 2 of PPSPS07 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-check 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 PE may provide misleading results. The analyst preparing the PE has several options for handling discontinuities that occur during outages. 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 limits 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 PE.

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 data required are the clock, ephemeris, and integrity (CEI) data. These area are contained in subframe 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

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 AOD offset (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 assumptions were discussed with systems engineers supporting 2 SOPS and are 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 2020 for all SVs except SVN 70/PRN 32. For each upload cutover we computed the AOD at the time of the upload cutover. We then computed the mean of these samples to determine an average AOD at the time of the upload cutover. There were 11590 samples with an average AOD of 962 sec (about 16 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 SPSPS20 provides usage assumptions for the SPS PS, 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 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 SPSPS20 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 31 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, position truth is 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 rare 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 GPS Toolkit (GPSTk)[18]. 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 [14] 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 of which 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.

Appendix D

Acronyms and Abbreviations

Table D.1: List of Acronyms and Abbreviations

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
BCP	Broadcast Clock and Position
CEI	Clock, Ephemeris, and Integrity
CMPS	Civil Monitoring Performance Specification
CODE	Center For Orbit Determination Europe
DCB	Differential Code Bias
DECOM	Decommission (NANU Type)
DLR	Deutsche Forschungsanstalt für Luftund Raumfahrt (German Institute of Communications and Navigation)
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
GPS	Global Positioning System
GPSTk	GPS Toolkit
HDOP	Horizontal Dilution Of Precision
ICD	Interface Control Document
IGG CAS	Institute of Geodesy and Geophysics of the Chinese Academy of Sciences in Wuhan
IGS	International GNSS Service
IODC	Issue of Data, Clock
IODE	Issue of Data, Ephemeris
IS	Interface Specification
ISB	Intersignal Bias
ISC	Intersignal Correction
JPL	Jet Propulsion Laboratory
LNAV	Legacy Navigation Message
LSB	Least Significant Bit
MCS	Master Control Station
MSB	Most Significant Bit
MSI	Misleading Signal Information
MSN	Monitor Station Network
NANU	Notice Advisory to Navstar Users
NAV	Navigation Message
NGA	National Geospatial-Intelligence Agency
NMCT	Navigation Message Correction Table
NTE	Not to Exceed

OA	Operational Advisory
ORD	Observed Range Deviation
PDOP	Position Dilution of Precision
PE	Precise Ephemeris
PNT	Position, Navigation, and Timing
PPS	Precise Positioning Service
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
SINEX	Station Independent Exchange Format
SIS	Signal-in-Space
SMC	Space and Missile Systems Center
SNR	Signal-to-Noise Ratio
SP3	Standard Product 3
SPS	Standard Positioning Service
SPS PS (SPSPS20)	2020 Standard Positioning Service Performance Standard
SV	Space Vehicle
SVN	Space Vehicle Number
TCP	Truth Clock and Position
TDOP	Time Dilution of Precision
T_{GD}	Group Delay Differential
UERAE	User-Equivalent Range Acceleration 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	United States Coast Guard
USNO	U.S. Naval Observatory
USSF	U.S. Space Force
USSF/SMC/ZAC-PNT	Capability Integration Division for PNT Mission Integration
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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