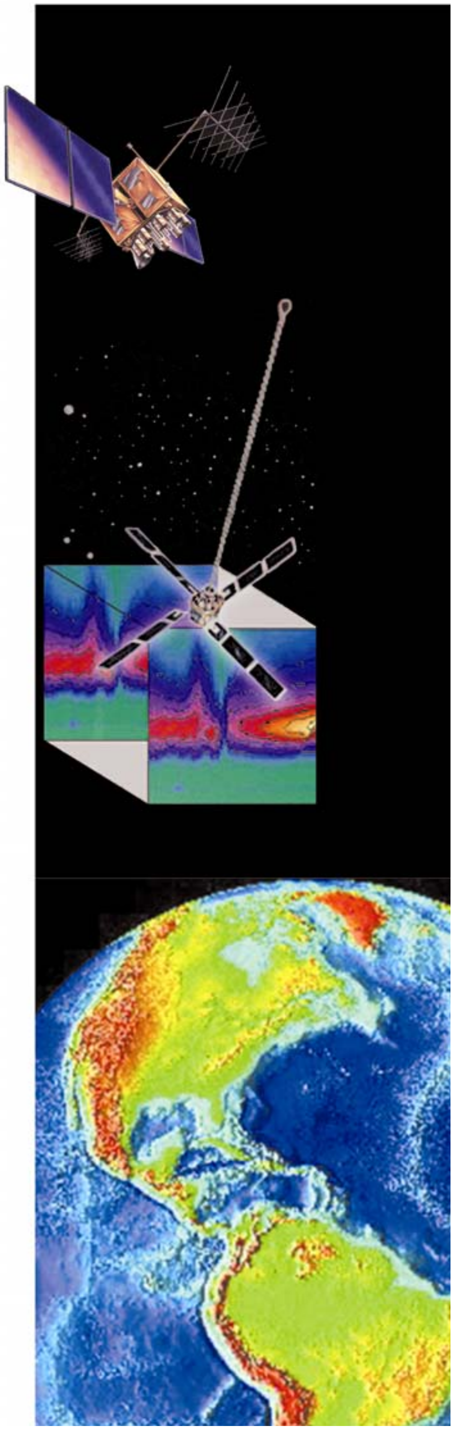
ARL
The University of Texas at Austin



An Analysis of Global Positioning System (GPS) Standard Positioning System (SPS) Performance for 2013

TR-SGL-15-02

31 July 2015

Brent A. Renfro,
Josh King,
Audric Terry,
Jeff Kammerman,
David Munton,
Johnathan York

Space and Geophysics Laboratory
Applied Research Laboratories
The University of Texas at Austin
P.O. Box 8029
Austin, TX 78713-8029

Contract: NAVSEA Contract N00024-01-D-6200
Task Order: 5101130

Distribution A: Approved for public release; Distribution is unlimited.

This Page Intentionally Left Blank

Executive Summary

Applied Research Laboratories, The University of Texas at Austin (ARL:UT) examined the performance of the Global Positioning System (GPS) throughout 2013 for the Global Positioning Systems Directorate (SMC/GP). This report details the results of that performance analysis. This material is based upon work supported by the US Air Force Space & Missile Systems Center Global Positioning Systems Directorate through NAVSEA Contract N00024-01-D-6200, task order 5101130, "GPS Signal and Performance Analysis".

Performance is characterized in terms of the 2008 Standard Positioning Service (SPS) Performance Standard (SPS PS). The performance standards provide the U.S. government's assertions regarding the expected performance of GPS. This report does not address each of the assertions in the performance standards. The emphasis is on 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 data archive.

The assertions evaluated include those associated with the accuracy, integrity, continuity, and availability of the GPS signal-in-space (SIS) and the position performance standards (through the position dilution of precision). Section 2 of the report includes a tabular summary of the assertions that were evaluated and a summary of the results. The remaining sections present details on the analysis associated with each assertion.

The report concludes that in 2013 all of the SPS PS assertions examined were met or exceeded.

Contents

1 Introduction **1**

2 Summary of Results **4**

3 Discussion of Performance Standard Metrics and Results **6**

3.1 SIS Accuracy 6

3.1.1 URE Over All AOD 7

3.1.2 URE at Any AOD 10

3.1.3 URE at Zero AOD 16

3.1.4 URE Bounding 16

3.2 SIS Integrity 17

3.3 SIS Continuity 17

3.4 SIS Availability 21

3.4.1 Per-slot Availability 21

3.4.2 Constellation Availability 21

3.4.3 Operational Satellite Counts 23

3.5 Position/Time Availability 25

3.5.1 PDOP Availability 25

3.5.2 Additional DOP Analysis 26

3.5.3 Position Service Availability 30

3.5.4 Position Accuracy 30

3.5.4.1 Results for Daily Average 34

3.5.4.2 Results for Worst Site 95^{th} Percentile 38

4 Additional Results of Interest **42**

4.1 Frequency of Different SV Health States 42

4.2 Age of Data 43
4.3 User Range Accuracy Index Trends 47
4.4 Extended Mode Operations 47

A URE as a Function of Age-of-Data **52**
A.1 Notes 52
A.2 Block IIA SVs 54
A.3 Block IIR SVs 57
A.4 Block IIR-M SVs 60
A.5 Block IIF SVs 62

B Limitations of URE Analysis **63**

C SVN to PRN Mapping for 2013 **66**

D NANU Activity in 2013 **68**

E Translation of URE Statistics Between Signals **70**
E.1 Group Delay Differential 70
E.2 Intersignal Bias 71
E.3 Adjusting PPS Dual-Frequency Results for SPS 72

List of Figures

1.1 Maps of the network of stations used as part of this report 3

3.1 Range of the monthly 95^{th} Percentile Values for all SV 11
3.2 Worst Performing Block IIA SV in Terms of Any AOD (SVN 35/PRN 30) 13
3.3 Worst Performing Block IIR/IIR-M SV in Terms of Any AOD (SVN 44/PRN 28) 13
3.4 Worst Performing Block IIF SV in Terms of Any AOD (SVN 65/PRN 24) 14
3.5 Best Performing Block IIA SV in Terms of Any AOD (SVN 26/PRN 26) 14
3.6 Best Performing Block IIR/IIR-M SV in Terms of Any AOD (SVN 55/PRN 15) 15
3.7 Best Performing Block IIF SV in Terms of Any AOD (SVN 62/PRN 25) 15
3.8 Daily Average Number of SVs Broadcasting a Healthy SIS 24
3.9 Count of Operational SVs by Day 25
3.10 Daily PDOP Metrics Using all SVs, 2013 29
3.11 Daily averaged position residuals computed using a RAIM solution . . . 36
3.12 Daily averaged autonomous position residuals using no data editing . . . 36
3.13 Pseudorange residuals for RAIM solution, enlarged to show variation in average residual 37
3.14 The non-edited pseudorange solution, enlarged to show variation in average residual. 37
3.15 Worst site 95^{th} percentile horizontal and vertical residuals for the RAIM Solution 39
3.16 Worst site 95^{th} percentile horizontal and vertical residuals with no data editing 39

4.1 Constellation Age of Data for 2013 45

C.1 PRN to SVN Mapping for 2013 67

D.1 Plot of NANU activity in 2013 69

List of Tables

2.1 Summary of SPS PS Metrics Examined for 2013 5

3.1 Monthly 95^{th} Percentile Values of SIS RMS URE for all SVs 9
3.2 Probability Over Any Hour of Not Losing Availability Due to Unscheduled Interruption. 20
3.3 Per-Slot Availability in 2013 for Baseline 24 Slots 22
3.4 Summary of PDOP Availability 26
3.5 Additional DOP Annually-Averaged Visibility Statistics for 2010 through 2013 28
3.6 Additional PDOP Statistics. 28
3.7 Organization of Positioning Results 33
3.8 Mean of Daily Average Position Errors for 2013 35
3.9 Median of Daily Average Position Errors for 2013 35
3.10 Maximum of Daily Average Position Errors for 2013 35
3.11 Standard Deviation of Daily Average Position Errors for 2013 35
3.12 Mean of Daily Worst Site 95^{th} Percentile Position Errors for 2013 41
3.13 Median of Daily Worst Site 95^{th} Percentile Position Errors for 2013 . . . 41
3.14 Maximum of Daily Worst Site 95^{th} Percential Position Errors for 2013 . . 41
3.15 Standard Deviation of Daily Worst Site 95^{th} Percentile Position Errors for 2013 41

4.1 Frequency of Health Codes 44
4.2 Age of Data of the Navigation Message by SV Type 45
4.3 Distribution of URA Index Values 48
4.4 Distribution of URA Index Values (As a Percentage of All Collected) . . 49
4.5 Summary of Occurrences of Extended Mode Operations 51

Chapter 1

Introduction

Applied Research Laboratories, The University of Texas at Austin (ARL:UT) examined the performance of the Global Positioning System (GPS) throughout 2013 for the Global Positioning Systems Directorate (SMC/GP). This report details the results of our performance analysis. This material is based upon work supported by the US Air Force Space & Missile Systems Center Global Positioning Systems Directorate through NAVSEA Contract N00024-01-D-6200, task order 5101130, "GPS Signal and Performance Analysis".

Performance is assessed relative to the commitments in the 2008 Standard Positioning Service (SPS) Performance Standard (SPS PS) [1]. (Hereafter the term SPS PS, or SPSPS08, are used when referring to the 2008 SPS PS.) Section 2 contains a tabular summary of performance stated in terms of the metrics stated in performance standards. Section 3 contains explanations and amplifications regarding the summary values. Section 4 details additional findings of the performance analysis.

The performance standards define the services delivered through the L1 C/A code signal. The metrics are limited to characterizing the signal in space (SIS) and do not address error sources such as atmospheric errors, receiver errors, or error due to the user environment (e.g. multipath errors). 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], and access to a data archive (such as that available via the International Global Navigation Satellite System (GNSS) Service (IGS)) [3]. The assertions examined include those related to URE, availability of service, and position domain standards (specifics can be found in Table 2.1).

Most of the analyses in this report are based on data collected by the National Geospatial-Intelligence Agency (NGA) Monitor Station Network (MSN) [4] and the IGS. The distribution of these stations is shown in Figure 1.1. The NGA archive is accessible as a consequence of ARL:UT's role as the lifecycle engineering organization for the NGA MSN. This archive is particularly useful for two reasons: (1.) It represents a highly-reliable set of data from a homogenous set of stations distributed in a manner that ensures continuous observation of all space vehicles (SVs) by multiple stations.

(2.) It includes a comprehensive set of navigation message data that captures the complete 300-bit subframes for nearly all unique sets of subframe 1, 2, 3 data and all unique sets of subframes 4, 5 data.

Data from a subset of the IGS were also considered for assertions in the areas of Continuity (3.3), Availability (3.4), and Position/Time Availability (3.5). The distribution of the IGS station used in this report is shown in Figure 1.1.

Several metrics in the performance standards are stated in terms of the Base 24 constellation of six planes and four slots/plane or the Expandable 24 constellation in which three of the 24 slots may be occupied by two SVs. Currently, there are more than 32 GPS SVs on-orbit. Of these, 31 or 32 SVs may be broadcasting at any time. Of the SVs on-orbit, 27 are located in the expandable 24 constellation. The SVs in excess of those located in defined slots are assigned to locations in various planes in accordance with operational considerations.

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 GPS SVs are referred to by PRN ID and by space vehicle number (referred to hereafter as PRN and SVN, respectively). As the number of active PRNs has increased to nearly the total available number, PRNs are now being used by multiple SVs within a given year. Therefore, the SVN represents a unique identifier for the vehicle under discussion. In general, we list the SVN first and the PRN second since the SVN is the unique identifier of the two. As an unintended side effect, this arrangement makes some of the tabular information appear in satellite Block order, which in turn makes some time-history comparisons more straightforward. The PRN-to-SVN relationships were provided by the MCS, however another useful summary of this information may be found through the USNO website [5].

Karl Kovach of Aerospace provided valuable assistance in interpreting the SPSPS08 metrics. John Lavrakas of Advanced Research Corporation and P.J. Mendicki of Aerospace Corporation have long been interested in GPS performance metrics and provided comments on the final draft. These inputs were very valuable, however, the results presented in this report are derived by ARL:UT and any errors are the responsibility of ARL:UT.

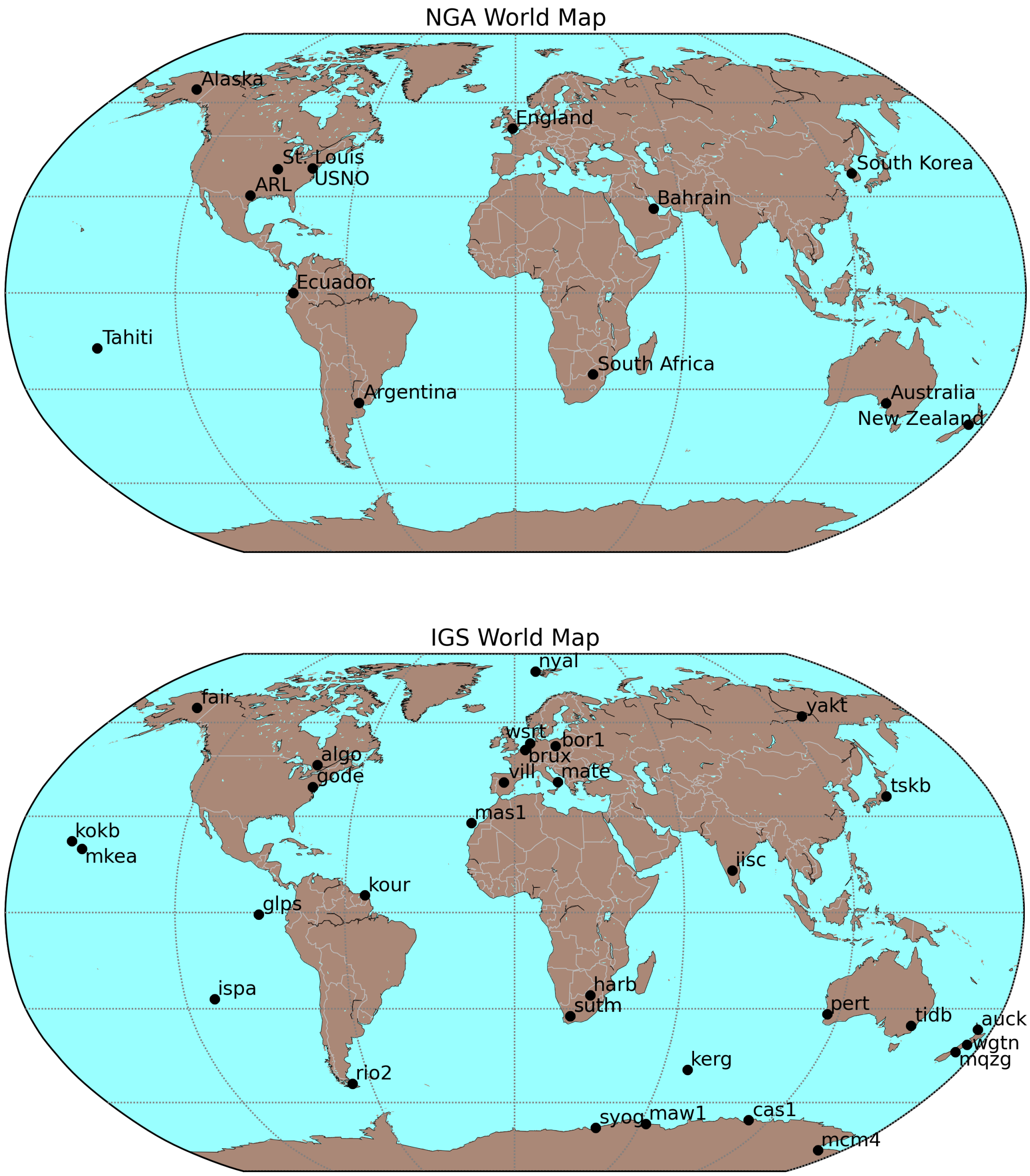


Figure 1.1: Maps of the network of stations used as part of this report. The upper map shows the distribution of NGA stations, and the lower map shows the distribution of the IGS stations used. Subsets of the IGS stations were used in some of the analyses.

Chapter 2

Summary of Results

All the SPS PS metrics examined in this report were met in 2013. Table 2.1 is a summary of the results. Details regarding each result may be found in the referenced sections.

Table 2.1: Summary of SPS PS Metrics Examined for 2013

SPSPS08 Section	SPS PS Metric	2013 Status
3.4.1 SIS URE Accuracy	≤ 7.8 m 95% Global average URE during normal operations over all AODs	✔✚
	≤ 6.0 m 95% Global average URE during normal operations at zero AOD	✔✚
	≤ 12.8 m 95% Global average URE during normal operations at any AOD	✔✚
	≤ 30 m 99.94% Global average URE during normal operations	✔✚
	≤ 30 m 99.79% Worst case single point average URE during normal operations	✔✚
3.5.1 SIS Instantaneous URE Integrity	≤ $1X10^{-5}$ Probability over any hour of exceeding the NTE tolerance without a timely alert	✔✚
3.6.1 SIS Continuity - Unscheduled Failure Interruptions	≥ 0.9998 Probability over any hour of not losing the SPS SIS availability from the slot due to unscheduled interruption	✔✚
3.7.1 SIS Per-Slot Availability	≥ 0.957 Probability that (a.) a slot in the baseline 24-slot will be occupied by a satellite broadcasting a healthy SPS SIS, or (b.) a slot in the expanded configuration will be occupied by a pair of satellites each broadcasting a healthy SIS	✔✚
3.7.2 SIS Constellation Availability	≥ 0.98 Probability that at least 21 slots out of the 24 slots will be occupied by a satellite (or pair of satellites for expanded slots) broadcasting a healthy SIS	✔✚
	≥ 0.99999 Probability that at least 20 slots out of the 24 slots will be occupied by a satellite (or pair of satellites for expanded slots) broadcasting a healthy SIS	✔✚
3.7.3 Operational Satellite Counts	≥ 0.95 Probability that the constellation will have at least 24 operational satellites regardless of whether those operational satellites are located in slots or not	✔✚
3.8.1 PDOP Availability	≥ 98% Global PDOP of 6 or less	✔✚
	≥ 88% Worst site PDOP of 6 or less	✔✚
3.8.2 Position Service Availability	≥ 99% Horizontal, average location	✔✚
	≥ 99% Vertical, average location	
	≥ 90% Horizontal, worst-case location	
	≥ 90% Vertical, worst-case location	
3.8.3 Position Accuracy	≤ 9 m 95% Horizontal, global average	✔✚
	≤ 15 m 95% Vertical, global average	
	≤ 17 m 95% Horizontal, worst site	
	≤ 37 m 95% Vertical, worst site	

✔✚ - Met or Exceeded

Chapter 3

Discussion of Performance Standard Metrics and Results

3.1 SIS Accuracy

SIS URE accuracy is asserted in Section 3.4 of the SPSPS08. The following standards (from Table 3.4-1) are considered in this report:

- $\leq$ 7.8 m 95% Global Average URE during Normal Operations over all AODs.
- $\leq$ 6.0 m 95% Global Average URE during Normal Operations at Zero AOD.
- $\leq$ 12.8 m 95% Global Average URE during Normal Operations at any AOD.
- $\leq$ 30 m 99.94% Global Average URE during Normal Operations.
- $\leq$ 30 m 99.79% Worst Case Single Point Average URE during Normal Operations.

The remaining standard associated with operations after extended periods without an upload is not practical to evaluate without data directly from the GPS Master Control Station.

The URE statistics presented in this report are based on a comparison of the satellite positions and clocks derived from the broadcast ephemeris against the satellite positions and clocks as contained in the NGA precise ephemeris. This is a useful approach, but one that has specific limitations, the most significant of which is that precise ephemeris does not well reflect the effect of individual discontinuities or large effects over a short time (such as a frequency step or clock runoff). A detailed discussion is included in Appendix B. Nonetheless use of precise ephemeris is appropriate given the long period of averaging implemented in determining URE, namely 30 days. Briefly, this approach allows the computation of URE without direct reference to observations from any particular ground sites, though the precise orbits carry an implicit network dependency.

The observations collected from tracking networks are used by NGA to develop the precise ephemeris (PE). Then the URE values are formed by using the broadcast ephemeris and the precise ephemeris to estimate a range residual. Given that both the broadcast ephemeris and the PE are referenced to the L1/L2 P(Y)-Code signal, the result is best characterized as the PPS dual-frequency URE. The SPS results are derived from the PPS dual-frequency results by a process described in Appendix E.

Throughout this section, there are references to the Instantaneous RMS SIS URE. This refers to the evaluation of the URE across the area of the service volume visible to the SV at a particular point 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 location there is a unique URE value based on geometric relationship between the SV and the location of interest. The "Instantaneous" means that no time averaging occurs. The "RMS" refers to taking the RMS of all the unique URE values across the area visible to the SV. This concept is explained in SPSPS08 Section A.4.11, and the relevant equation is presented in Appendix B of this report.

While Section 2 notes the SPSPS08 specifications have been met, the additional statistics and trends reported in this section provide both additional information and support for these conclusions.

3.1.1 URE Over All AOD

The performance standard URE metric that most closely matches a user's observations is the calculation of URE over all AODs. This is associated with the SPSPS08 Section 3-4 metric:

- $\leq$ 7.8 m 95% Global Average URE during Normal Operations over all AODs

This metric can be decomposed into several pieces in order to better understand the process.

- 7.8 m - This is the limit against which to test. The value is unique to the signal under evaluation.
- 95^{th} Percentile - This is the statistical measure applied to the data to determine the actual URE. In this case, there are a sufficiently large number of samples to allow direct sorting of the results and selection of the 95^{th} percentile.
- Global Average URE This is another term for the Instantaneous RMS SIS URE, a statistical quantity representing the average URE across the area of the service volume visible to the SV at a given point in time. The expression used to compute this quantity is provided in Appendix B.
- Normal Operations - This is a constraint related to normal vs. extended mode operations. See IS-GPS-200 20.3.4.4 [2]. There were occasional periods when

individual SVs operated in Short-term Extended Operations in 2013 (this is discussed in Section 4.4) but these periods do not affect the results.

- over all AODs - This constraint means that the Global Average URE will be considered at each evaluation time regardless of the age of data (AOD) at the evaluation time. A more detailed explanation of the AOD and how this quantity is computed can be found in Section 4.2.

In addition there are two general statements in Section 3.4 that have a bearing on this calculation.

- These statistics only include periods when each SV was healthy.
- 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" (SPSPS08 Section 3.4, Note 1) Therefore the statistics will be computed over a monthly period and not daily. Since outages do occur, we have computed the statistic for each month, regardless of the number of days of availability, but identified these values when displayed.

Based on this set of assumptions and constraints, the monthly 95^{th} percentile values of the RMS SIS URE were computed for each SV as provided in Table 3.1. Values computed for incomplete months are shown with shaded cells. For each SVN we show the worst of these values across the year in red. The gaps in URE indicate that the satellite was unusable, decommissioned (SVN35), or not yet launched (SVN66). Note that none of the values in this table exceed the threshold of 5.9 m. The annual 95^{th} Percentile values for 2013 are provided in Table 3.1. In all cases, no values exceed 7.8 m and so this requirement is met for 2013.

Figure 3.1 provides a summary of these results for the entire constellation. For each SVN, shown along the x-axis, the median value of the monthly 95^{th} percentile SIS URE is computed and displayed as a point. The full range of the annual monthly 95^{th} percentile SIS URE is shown by the vertical bars. Color distinguishes between the Block II/IIA, Block IIR, Block IIR-M, and Block IIF SVs. The red horizontal line at 7.8m indicates the upper bound given by the SPSPS08 Section 3-4 performance metric.

A number of points are evident from Figure 3.1.

1. All SVs meet the performance specification of the SPSPS08, 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 a factor of 2 or more smaller than the threshold.

Table 3.1: Monthly 95^{th} Percentile Values of SIS RMS URE for all SVs. No values exceed 7.8m. 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 RMS URE for a given SV are colored red. The column labeled "2013" is the 95^{th} Percentile over the year. The four rows at the bottom are the monthly 95^{th} Percentile values over various sets of SVs.

SVN	PRN	Block	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	2013
23	32	IIA	1.46	1.34	1.20	1.42	1.33	1.64	1.46	1.73	1.22	1.24	1.36	1.52	1.42
26	26	IIA	1.11	1.18	1.09	1.17	1.27	1.51	1.16	1.02	1.16	1.30	1.27	1.64	1.26
33	3	IIA	2.89	2.65	2.68	2.53	2.49	2.45	2.51	2.60	2.41	2.53	2.70	2.61	2.61
34	4	IIA	1.85	1.64	1.72	1.86	1.88	2.14	2.14	1.82	2.05	1.88	1.66	1.84	1.89
35	30	IIA	3.18	3.12	3.18										3.16
36	6	IIA	1.82	1.89	2.04	2.10	2.46	1.96	2.02	1.92	1.86	1.82	1.82	1.75	2.00
38	8	IIA	2.67	2.83	2.75	2.65	2.56	2.76	2.65	2.80	2.47	2.91	2.77	2.59	2.71
39	9	IIA	2.51	2.60	2.80	2.78	2.90	2.64	2.76	2.85	2.62	2.65	2.61	2.69	2.71
40	10	IIA	2.54	2.36	2.65	2.65	2.62	2.46	2.29	2.72	2.60	2.55	2.69	2.62	2.58
41	14	IIR	1.11	1.08	1.05	1.07	0.96	1.06	1.05	1.34	1.08	1.00	0.95	0.96	1.05
43	13	IIR	1.20	1.05	1.38	1.13	1.16	1.16	1.18	1.05	1.10	1.11	1.25	1.18	1.17
44	28	IIR	2.55	2.50	2.67	2.64	2.46	2.50	2.40	2.29	2.30	2.44	2.32	2.48	2.46
45	21	IIR	0.99	0.95	1.04	1.00	0.98	0.94	0.94	0.96	1.03	0.97	0.98	1.02	0.99
46	11	IIR	1.86	1.40	1.43	1.49	1.30	1.44	1.66	1.56	1.62	1.63	1.29	1.66	1.52
47	22	IIR	1.74	1.72	1.65	2.13	2.19	1.88	1.67	1.84	2.04	1.98	1.83	1.86	1.87
48	7	IIR-M	1.06	1.16	1.07	1.09	1.06	1.16	1.08	1.17	1.14	1.20	1.15	1.23	1.13
50	5	IIR-M	0.95	1.01	0.96	1.01	0.94	0.91	0.95	0.91	0.94	0.99	0.96	0.96	0.96
51	20	IIR	0.97	0.97	0.96	1.00	0.97	0.93	0.96	0.95	0.95	0.98	0.93	0.92	0.96
52	31	IIR-M	1.26	1.46	1.20	1.28	1.28	1.37	1.58	1.41	1.41	1.31	1.30	1.41	1.35
53	17	IIR-M	2.06	1.64	1.44	1.47	1.81	1.33	2.19	1.78	1.52	1.44	1.48	1.61	1.64
54	18	IIR	0.91	0.93	1.32	0.98	1.02	0.99	1.22	1.01	0.96	0.94	0.97	1.08	1.02
55	15	IIR-M	0.93	0.90	0.90	0.91	0.93	0.92	0.94	0.89	0.94	0.91	0.93	0.92	0.92
56	16	IIR	0.91	0.90	0.93	0.96	0.91	0.97	0.90	0.91	0.93	0.96	0.96	0.95	0.93
57	29	IIR-M	1.46	1.46	1.61	1.38	1.45	1.38	1.55	1.48	1.46	1.29	1.78	1.45	1.48
58	12	IIR-M	0.95	0.96	0.93	0.95	0.94	0.92	0.93	0.92	0.92	0.97	0.93	0.98	0.94
59	19	IIR	0.99	1.02	0.97	1.07	0.96	0.93	0.96	1.02	1.01	0.96	0.97	1.00	0.98
60	23	IIR	0.94	0.93	0.93	0.92	0.99	0.94	0.95	0.91	0.90	0.93	0.91	0.97	0.94
61	2	IIR	0.97	1.00	1.02	0.99	1.01	0.95	1.01	1.02	1.00	0.95	1.02	1.05	1.00
62	25	IIF	0.93	0.94	0.94	0.96	1.00	0.93	0.94	0.99	0.98	1.10	1.00	0.98	0.97
63	1	IIF	1.01	0.96	1.04	1.04	0.94	0.92	0.92	0.97	0.99	0.93	0.97	1.16	1.00
65	24	IIF	2.49	2.56	2.56	2.56	2.36	2.42	2.62	2.42	2.46	2.58	2.44	2.23	2.50
66	27	IIF						1.33	1.30	1.04	0.98	0.94	0.96	1.03	1.06
Block IIA			2.46	2.44	2.53	2.35	2.39	2.33	2.32	2.41	2.26	2.34	2.40	2.36	2.39
Block IIR/IIR-M			1.31	1.28	1.28	1.23	1.26	1.23	1.32	1.31	1.24	1.28	1.29	1.30	1.28
Block IIF			1.86	1.90	2.01	1.83	1.81	1.78	1.80	1.68	1.69	1.94	1.72	1.44	1.78
All SVs			1.88	1.85	1.95	1.78	1.85	1.77	1.78	1.82	1.73	1.78	1.79	1.77	1.81

2. As a general rule, the newer satellites outperform the older Block IIA satellites in terms of the 95^{th} Percentile SIS URE metric. The average performance of the Block IIA SVs nearly a meter higher than that of the Block IIR, IIR-M, and IIF SVs if SVN 65/PRN 24 is omitted (see Table 3.1).

3. For most of the SVs, the value of the 95^{th} Percentile SIS URE metric is relatively stable over the course of the year, as indicated by relatively small range bars.

4. For some SVs there are large range extents for the bars. This includes SVNs 36 and 53, which both have spreads of URE values of nearly 1 m.

5. The "best" SVs appear to be the Block IIR, Block IIR-M, and Block IIF which cluster below the 1.0 m level (actually close to the .5 m level), and whose range variation is small. This includes SVNs 45, 48, 50, 51, 55, 56, 58, 59, 60, 61, 62, and 63.

6. The values for SVN 65 are noticeably different than the other Block IIF SVs. It is also the only Block IIF SV operating on a Cesium frequency standard.

3.1.2 URE at Any AOD

The next URE metric considered is the calculation of URE at any AOD. This is associated with the following SPSPS08 Section 3-4 metrics:

- $\leq$ 12.8 m 95% Global Average URE during Normal Operations at any AOD

This metric may be decomposed in a manner similar to the previous metric. The key difference is the term "at any AOD" and the change in the threshold values. 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 required statistic should be $\leq$ 12.8 m. See Section 4.2 for a discussion of how the AOD is computed.

To examine this requirement, the same set of 30s Instantaneous RMS SIS URE values used in Section 3.1.1 was analyzed using a bin approach. The details are covered in Appendix A. In summary, the RMS SIS URE values were divided into bins based on 15 minute intervals of AOD. The 95^{th} percentile values for each bin were selected and the results were plotted as a function of the AOD.[1]

Figures 3.2 through Figure 3.7 show two curves: shown in blue is the 95^{th} Percentile URE vs. AOD (in hours), and shown in green the count of points in each bin as a function of AOD. For satellites that are operating on the normal pattern (roughly one

[1]Bins with a small number of points are suppressed from the plots. Such bins tend to occur at the right most end of the plots and the results are sometimes dominated by outliers. To avoid such misleading distractions, the plotting tool determines the bin with the maximum number of points, then plot bins from left-to-right until a bin is reached with $\leq$ 10% of the number of points in the bin with the maximum number of points.

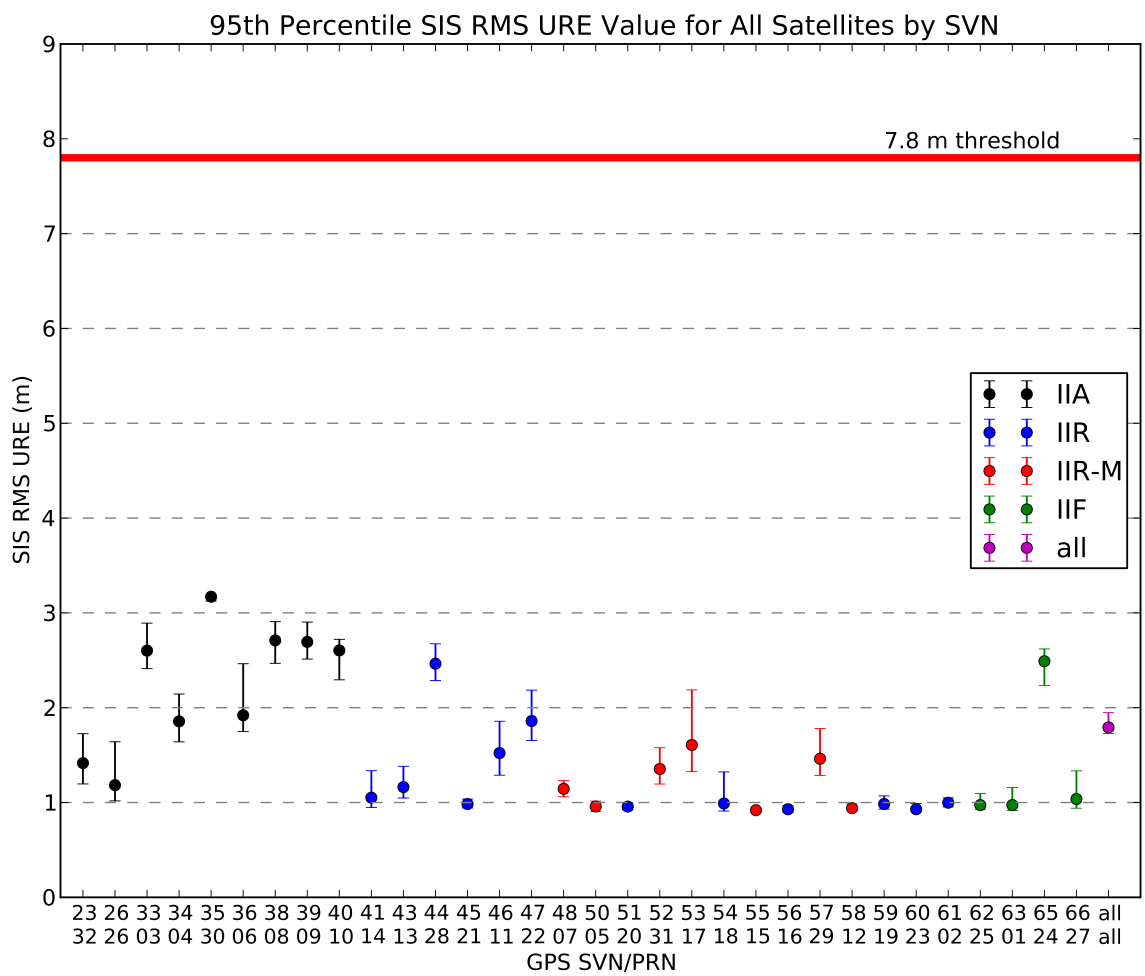


Figure 3.1: Range of the monthly 95^{th} Percentile Values for all SV. Each SVN with valid data is shown sequentially along the x-axis. The median value of the monthly 95^{th} Percentile SIS URE displayed as a point along the vertical axis. The full range of the monthly 95^{th} Percentile SIS URE for 2013 is shown by the vertical bars. Color distinguishes between the Block II/IIA, Block IIR, Block IIR-M, and Block IIF SVs. The red horizontal line at 7.8 m indicates the upper bound given by the SPSPS08 Section 3-4 performance metric, from which it is clear that the performance metric is met for the year. The markers for "all" represent the monthly 95^{th} Percentile values across all satellites.

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 30s estimates in a 15 minute bin (30) by the number of day in the year (365). The result is 10950, or a little less than 12000. 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 declining 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 Figure 3.2 through 3.7 and the figures in Appendix A have been constrained to a constant value to aid in comparisons between the charts. This means that satellites that were only operational for part of the year (e.g. SVN 35, SVN 66) will have a lower number of points per bin than the nominal.

The first three plots show the worst performing (i.e., highest URE values) Block IIA, Block IIR/IIR-M, and Block IIF SVN, SVN 35, SVN 44, and SVN 65 respectively. Note that the distribution of AOD samples for SVN 35 is concentrated at shorter values of AOD, which indicates that frequent uploads are occurring. SVN 44 shows similar behavior, but at a much larger AOD, indicating less frequent additional uploads.

The best performers for Block IIA, Block IIR/IIR-M, and Block IIF are shown in Figures 3.5 through 3.7. These figures show a very flat distribution of AODs, and the UREs appear to degrade roughly linearly with time, at least out to the point that the distribution (represented by the green curve) shows a marked reduction in the number of points.

The plots for all satellites are contained in Appendix A. A review of the full set leads to the conclusion that the behaviors described in the previous two paragraphs are not block-specific but are rather characteristic of age or the type of frequency standard. For example, five of the nine Block IIA satellites exhibit evidence of more frequent uploads as indicated by an uneven distribution of observation across the time bins. The remaining four Block IIA satellites, each of which operate on older Cesium frequency standards, exhibit somewhat faster URE growth than the later satellites operating on Rubidium clocks, but the distribution of points is still roughly even across the day. Among the Block IIF SVs, The rate of URE growth is noticeably higher for the single satellite that uses a Cesium frequency reference. While there are noticeable differences between individual satellites, all the results are well within the assertion for this metric.

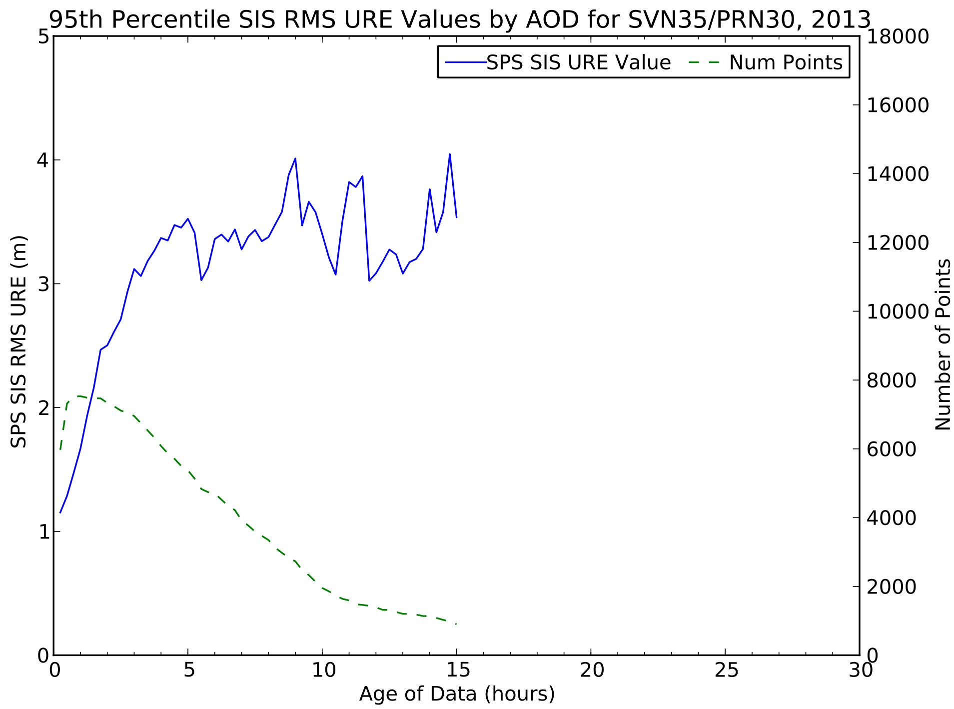


Figure 3.2: Worst Performing Block IIA SV in Terms of Any AOD (SVN 35/PRN 30)

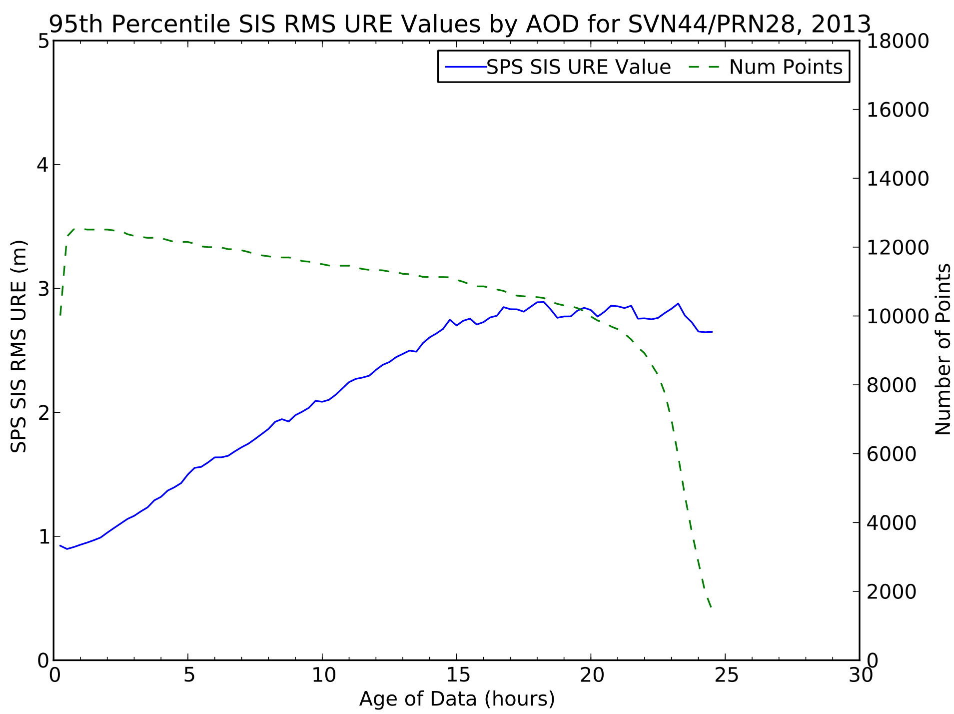


Figure 3.3: Worst Performing Block IIR/IIR-M SV in Terms of Any AOD (SVN 44/PRN 28)

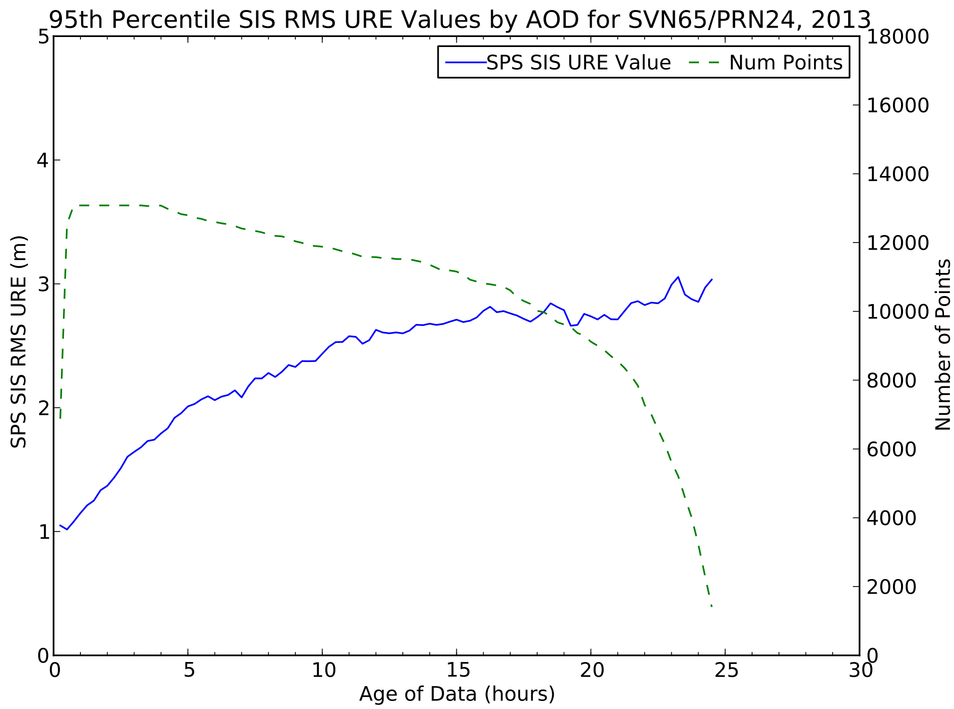


Figure 3.4: Worst Performing Block IIF SV in Terms of Any AOD (SVN 65/PRN 24)

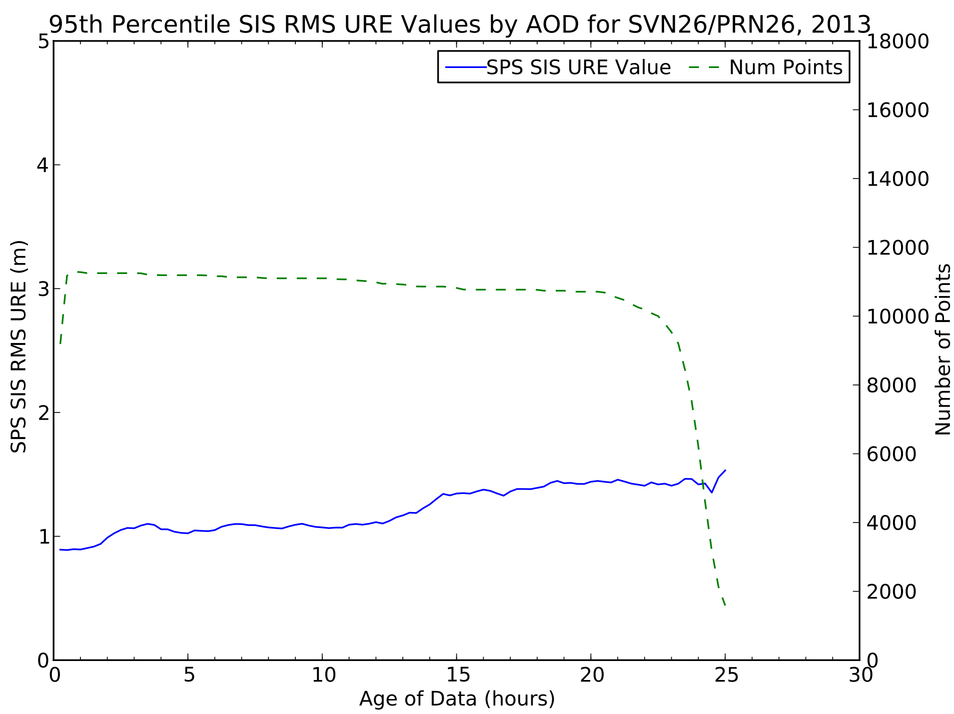


Figure 3.5: Best Performing Block IIA SV in Terms of Any AOD (SVN 26/PRN 26)

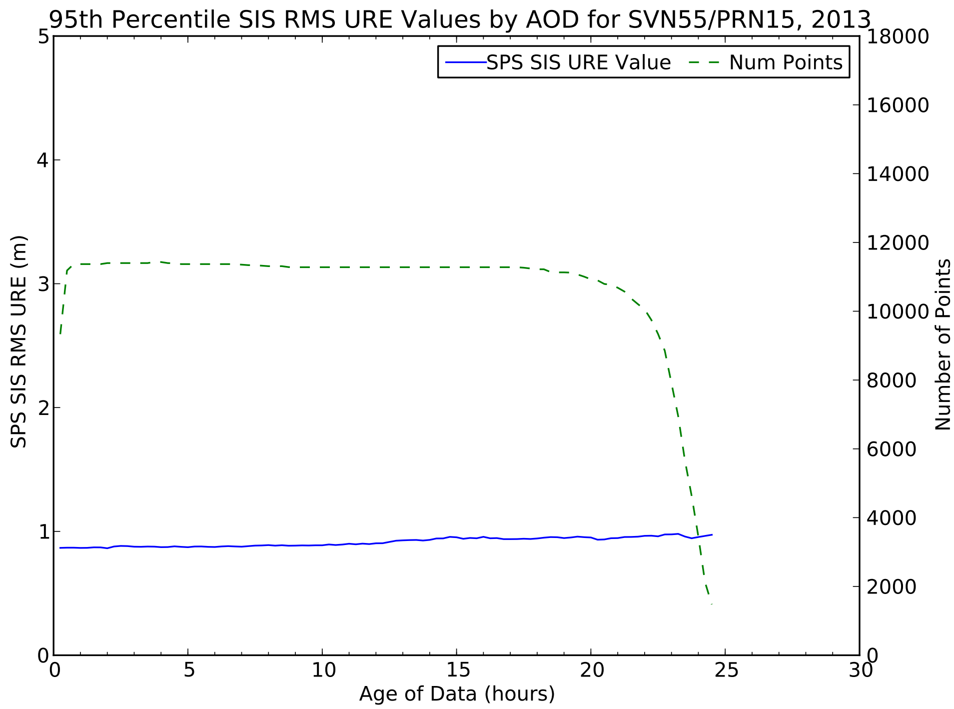


Figure 3.6: Best Performing Block IIR/IIR-M SV in Terms of Any AOD (SVN 55/PRN 15)

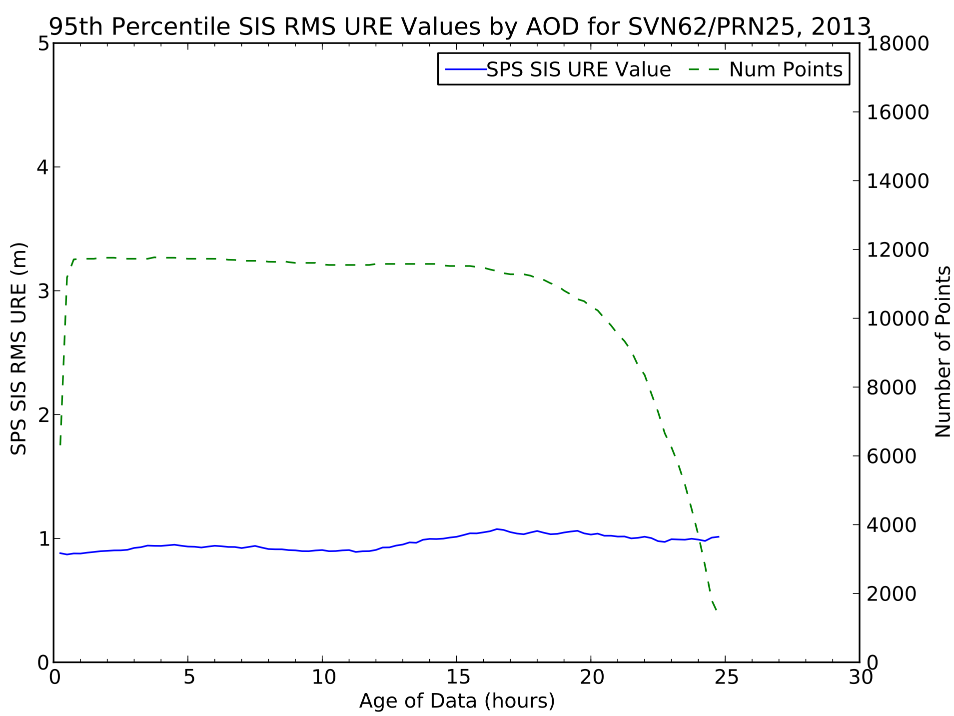


Figure 3.7: Best Performing Block IIF SV in Terms of Any AOD (SVN 62/PRN 25)

3.1.3 URE at Zero AOD

Another URE metric considered is the calculation of URE at Zero AOD. This is associated with the SPSPS08 Section 3-4 metric

- ≤ 6.0 m 95% Global Average URE during Normal Operations at Zero AOD

This metric may be decomposed in a manner similar to the previous two metrics. The key difference is the term "at Zero AOD" and the change in the threshold values.

The broadcast ephemeris is never available to user equipment at Zero AOD simply 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 95% SIS RMS URE value at 15 minutes AOD. These values are represented by the left-most data point on the red lines shown in Figure 3.2 through Figure 3.7. The ZAOD values should be slightly better 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 6.0 m value associated with the assertion. Therefore the first of the assertions is considered fulfilled.

3.1.4 URE Bounding

The SPSPS08 asserts the following requirements for single frequency C/A code:

- ≤ 30 m 99.94% Global Average URE during Normal Operations.
- ≤ 30 m 99.79% Worst Case Single Point Average URE during Normal Operations.

As noted earlier the thirty second instantaneous SIS RMS URE values were used to evaluate these requirements. 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 B. As a result of these limitations, the UREs were only used as a screening tool to identify possible violations of this requirement. Possible candidate events were then screened further by examining the observed range deviations (ORDs) to determine actual values during the event.

The ORDs are formed using the observation data collected to support the position accuracy analysis described in Section 3.5.4. In the case of ORDs, the observed range is differenced from the range predicted by subtracting the known station position from the predicted SV location. 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.

The thirty second instantaneous SIS RMS URE values and the 30s ORD values throughout 2013 were examined to determine if any values exceeded 30m. No such values were found. As a result, these assertions are considered satisfied.

3.2 SIS Integrity

Under the heading of SIS Integrity, the SPSPS08 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 During Normal Operations.

The associated conditions and constraints include a limitation to healthy SIS, an NTE tolerance ±4.42 times the upper bound on the URA currently broadcast, and a worst case for a delayed alert of 6 hours.

To estimate the worst-case probability of users experiencing misleading signal information (MSI), note that immediately below SPSPS08 Table 3.5-1 is an explanation that for a 32 SV constellation (full broadcast almanac) the corresponding average annual number of SPS SIS instantaneous URE integrity losses is 3. Assuming each of the 3 losses lasts no more than 6 hours, the fraction of time in which MSI will occur is 0.002.

This assertion was verified using two methods. In the first method, the thirty second Instantaneous SIS RMS URE values generated to build Table 3.1 were examined to determine the number of values that exceed 4.42 times the URA.

By itself, this is not conclusive. As noted in Appendix B, experience has shown that when a SV event produces a discontinuity or a large effect over a short time (such as a frequency step or a clock run-off) the precise ephemeris may yield poor results in the area of the discontinuity depending on how the orbit analyst addresses the discontinuity, the duration the SV was set unhealthy, and the nature of the interpolation algorithm used with the precise ephemeris. This limitation is overcome by also examining the ORDs.

Screening the thirty second instantaneous SIS RMS URE values for 2013 and the ORD data did not reveal any events for which this threshold was exceeded. So this requirement is considered satisfied.

3.3 SIS Continuity

The metric is stated in SPSPS08 Table 3.6-1 as follows:

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

The Conditions and Constraints note the following.

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

It is worth pointing out that the notion of SIS continuity is slightly more complex for an expandable slot, since multiple SVs are involved. Following SPSPS08 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 the logical "and" of the availability of the individual SVs.

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 this 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 believed to be the correct value to compare to the SPS PS 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 how to derive information on interruptions from the available data.
3. We must know how to determine scheduled vs. unscheduled interruptions.

The first of these, the SV/slot assignments map, was provided to ARL:UT by Aerospace Corp. analysts supporting 2^{nd} Space Operations Squadron (2 SOPS). The assignments were provided as a set of daily SV assignments for the year.

For purposes of this report, interruptions were considered to have occurred if one or more of the SV(s) assigned to the given slot is (are) unhealthy in the sense of SPSPS08 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 visiblity (and at least 90% three-station visibility) with redundant receivers at each station. Therefore, if no data for a satellite are received for a specific time, it is highly likely that the satellite was not transmitting at that time. The 30s RINEX [6] observation files from this network were examined for each measurement interval (i.e. every 30s) for each SV. If at least one receiver collected a pseudorange data set on L1 C/A, L1 P(Y), 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 30s IGS data collected to support the position accuracy estimates (Section 3.5.4) 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 year was examined, and if any 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 the times and durations of interruptions. Once this was done, the NANUs effective in 2013 were reviewed to determine which of these interruptions could be considered scheduled interruptions as defined in SPSPS08 Section 3.6. The scheduled interruptions were removed from consideration with respect to counting interruptions. 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.

Unscheduled interruptions are not always documented with a NANU. A small number of short-duration outages not covered by NANUs were observed. When such outages occurred on satellites that are assigned to one of 24 slots, the outage was counted in evaluating this assertion.

Scheduled interruptions as defined in the ICD-GPS-240 [7] have a nominal notification time of 96 hours prior to the outage. Following the SPSPS08 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. The time from the start of the interruption to the 48 hour after notification time can be considered as a potential unscheduled interruption (for continuity purposes). However, a healthy SIS must exist at the start of any hour for an interruption to be considered to occur.

For scheduled interruptions that extend beyond the period covered by a FCSTDV or FCSTMX NANU, the uncovered portion will be considered an unscheduled interruption. However, if a FCSTEXTD NANU extending the length of a scheduled interruption is published 48 hours in advance of the effective time of extension, the interruption will remain categorized 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.

Table 3.2 is a summary of the results of the assessment of SIS continuity. Interpreting the metric as being averaged over the constellation, the constellation exceeded the goal of 0.9998 probability of not losing the SPS SIS availability due to a unscheduled interruption.

Table 3.2: Probability Over Any Hour of Not Losing Availability Due to Unscheduled Interruption.

Plane-Slot[a]	# of Hours with the SPS SIS available at the start of the hour	# of Hours with Unscheduled Interruption[b]	Fraction of Hours in Which Availability was Not Lost	SVN (PRN)[c]
A1	8756	0	1.00000	65(24)
A2	8753	0	1.00000	52(31)
A3	8753	0	1.00000	38(08)
A4	8760	0	1.00000	48(07)
B1	8760	2	0.99977	35(30) 56(16)
B2	8749	0	1.00000	62(25)
B3	8760	0	1.00000	44(28)
B4	8753	0	1.00000	58(12)
C1	8755	0	1.00000	57(29)
C2	8736	4	0.99954	33(03) 66(27)
C3	8760	0	1.00000	59(19)
C4	8755	0	1.00000	53(17)
D1	8714	1	0.99989	61(02)
D2	8739	0	1.00000	46(11) 63(01)
D3	8760	0	1.00000	45(21)
D4	8748	0	1.00000	34(04)
E1	8754	0	1.00000	51(20)
E2	8760	0	1.00000	47(22)
E3	8753	0	1.00000	50(05)
E4	8754	0	1.00000	54(18)
F1	8755	0	1.00000	41(14)
F2	8754	0	1.00000	26(26) 55(15)
F3	8754	0	1.00000	43(13)
F4	8760	0	1.00000	60(23)
All Slots	210055	7	0.99996	

[a] B1,D2, and F2 are expandable slots and may have more than one SV assigned

[b] Number of hours in which (1.) an SV transmitted navigation message with subframe 1 health bits set to other than all zeroes without a scheduled outage, (2.) signal lost without a scheduled outage, or (3.) the URE NTE tolerance was violated.

[c] In some cases, more than one SV occupied a slot location during 2013

To put this in perspective, there were 8760 hours in 2013. The required probability of not losing SPS SIS availability implies that there be less than $8760 \times (1 - 0.9998) = 1.75$ hours that experience unscheduled interruptions in a year. If this were a per-slot metric, this would mean no slot may experience more than one unscheduled interruption in a year. The maximum number of unscheduled interruptions over the 24 slot constellation is given by $8760 \times 24 \times (1 - 0.9998) = 42$ 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 3.2, across the constellation slots the total number of hours lost was 7. This is smaller than the maximum number of hours of unscheduled interruptions (42) available in order to meet the metric (see the previous paragraph), and leads to empirical value for the fraction of hours in which SIS continuity was maintained of 0.99996. Therefore, this assertion is considered fulfilled in 2013.

3.4 SIS Availability

3.4.1 Per-slot Availability

The SPSPS08 Section 3.7.1 makes two linked statements in this area.

- $\geq$ 0.957 Probability that a Slot in the Baseline 24-Slot Configuration will be Occupied by a Satellite Broadcasting a Healthy 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 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.

As noted in the previous section, the SV/slot assignments map was provided to ARL:UT by Aerospace Corp. analysts and were provided as a set of daily SV assignments for the year.

This metric was verified by examining the status of each SV in the Baseline 24- Slot configuration (or pair of SVs in an Expandable Slot) at every 30 second 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 monitor station networks were examined to verify that the SV was broadcasting a trackable signal at the time. The results are summarized in Table 3.3. The average availability for the constellation was 0.997, exceeding the threshold of 0.957. The availability values for all slots were better than the threshold. Therefore the assertion being tested in this section was met.

3.4.2 Constellation Availability

The SPSPS08 makes two linked statements in this area.

- $\geq$ 0.98 Probability that at least 21 Slots out of the 24 Slots will be Occupied Either by a Satellite Broadcasting a Healthy SPS SIS in the Baseline 24-Slot

Table 3.3: Per-Slot Availability in 2013 for Baseline 24 Slots. For each slot there were 1054080 total 30 second epochs.

Plane-Slot[a]	# Missing Epochs	Available	SVN (PRN)[b]
A1	420	0.999600	65(24)
A2	848	0.999193	52(31)
A3	810	0.999229	38(08)
A4	0	1.000000	48(07)
B1	0	1.000000	35(30) 56(16)
B2	1214	0.998845	62(25)
B3	0	1.000000	44(28)
B4	761	0.999276	58(12)
C1	600	0.999429	57(29)
C2	2841	0.997297	33(03) 66(27)
C3	0	1.000000	59(19)
C4	625	0.999405	53(17)
D1	5526	0.994743	61(02)
D2	2465	0.997760	46(11) 63(01)
D3	0	1.000000	45(21)
D4	1442	0.998628	34(04)
E1	645	0.999386	51(20)
E2	0	1.000000	47(22)
E3	857	0.999185	50(05)
E4	655	0.999377	54(18)
F1	606	0.999424	41(14)
F2	801	0.999238	26(26) 55(15)
F3	648	0.999384	43(13)
F4	0	1.000000	60(23)
All Slots	21654	0.999142	

[a] B1,D2, and F2 are expandable slots and may have more than one SV assigned
[b] In some cases, more than one SV occupied a slot location during 2013

Configuration or by a Pair of Satellites Each Broadcasting a Healthy SPS SIS in the Expanded Slot Configuration

- $\geq$ 0.99999 Probability that at least 20 Slots out of the 24 Slots will be Occupied Either by a Satellite Broadcasting a Healthy 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

To evaluate this metric the subframe 1 health condition and the availability of signal was evaluated for each SV every 30 seconds for all of 2013. 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. If an SV belonged to baseline slot, the slot was counted as occupied. If a SV belonged to an expandable slot, the slot was not counted as occupied until a second healthy SV was found for this 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. Unsurprisingly, the value for 2013 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 30s interval the number of SVs broadcasting a healthy SIS was counted. This was both for count of occupied slots and for the number of SVs. The daily averages as a function of time are shown in Figure 3.8. As is clear, the number of occupied slots always exceeds 21.

The Number of Occupied Slots shown in Figure 3.8 drops from 24 to 23 in late March 2013 and remains at 23 for the remainder of 2013. This is a result of the fact SVN 35/PRN 30 was first set unhealthy and then decommissioned. SVN 35/PRN 30 was assigned to B1F, an expandable slot. After SVN 35/PRN 30 was no longer available there is no indication that the control segment moved another SV into that location prior to 2014, nor was there notification that the slot had reverted to a normal slot. While this yields the counter-intuitive result that the number of occupied slots is 23, it is neither a violation of Constellation Availability assertions (described above) nor does it present a problem for the user (at least in this case). As shown by the DOP values described in Section 3.5.1, even with this expandable slot only half-filled, the DOP values were excellent throughout 2013.

3.4.3 Operational Satellite Counts

In Table 3.7-3, SPSPS08 states

- $\geq$ 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.

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

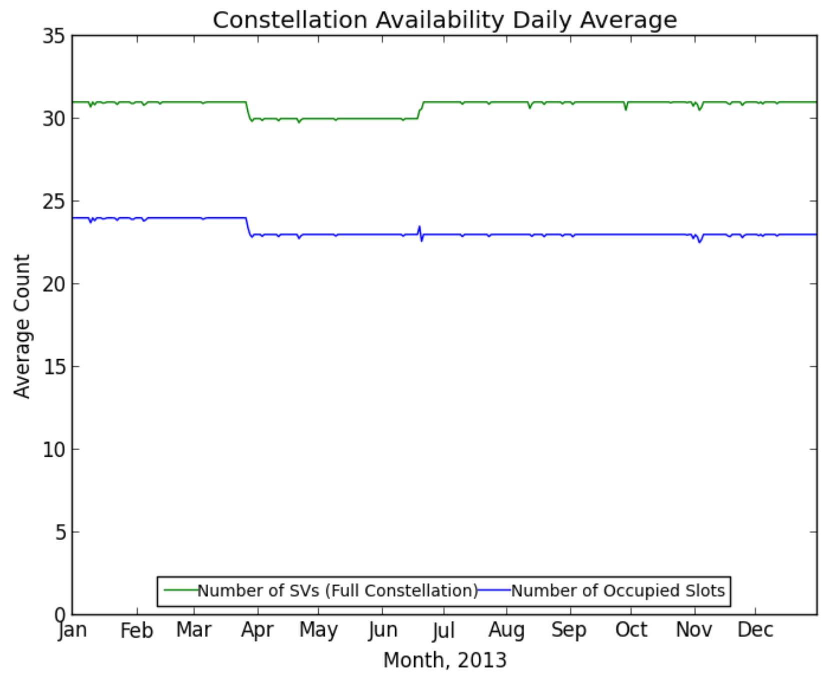


Figure 3.8: Daily Average Number of SVs Broadcasting a Healthy SIS

> "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 3.4.1 and 3.4.2, we conclude that the probability associated with this metric is 1.00 for 2013. However, the navigation message was examined as a means of checking for consistency in the navigation message. The process selected an almanac for each day in 2013. 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 may 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 3.9. This plot is very similar to the full constellation healthy satellite count shown in Figure 3.8. The almanac health data are not updated as frequently as those in Subframe 1. As a result, the plot in Figure 3.8 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 3.8, such effects are averaged over the day, yielding a higher availability.

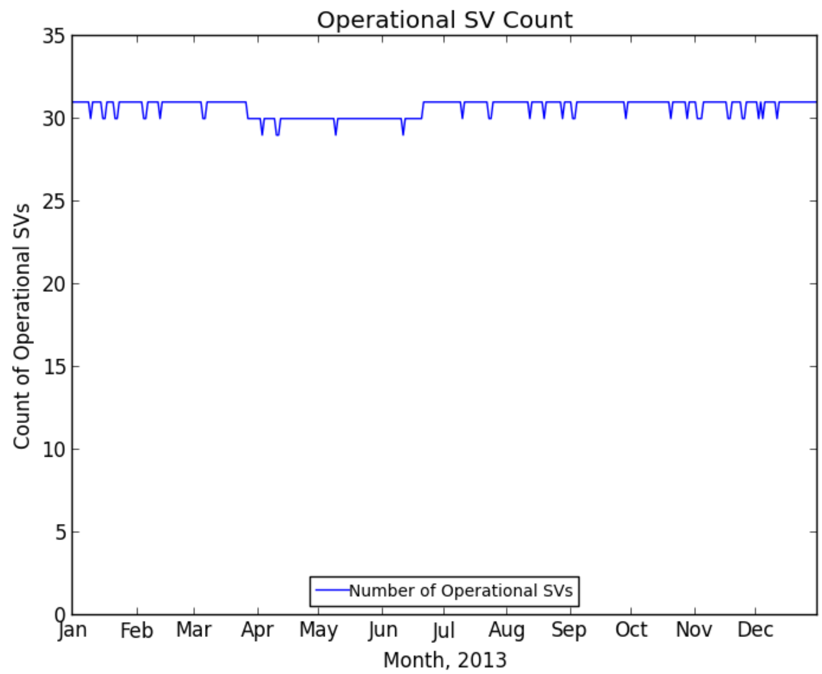


Figure 3.9: Count of Operational SVs by Day

3.5 Position/Time Availability

3.5.1 PDOP Availability

Given representative user conditions and considering any 24 hour interval the SPSPS08 calls for:

- $\geq$ 98% global PDOP of 6 or less, and
- $\geq$ 88% worst site PDOP of 6 or less.

These assertions were verified empirically throughout 2013 using a regularly 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. The grid was $111km \times 111km$ (roughly $1^{\circ} \times 1^{\circ}$ at the Equator, larger in longitude as the latitude increases). The time started at 0000Z each day and stepped through the entire day at five minute intervals (288 points/day, or more generically, N_t). The overall process followed is similar to that defined in Section 5.4.6 of the GPS Civil Monitoring Performance Standard (CMPS) [8].

The PDOP values were formed using the traditional PDOP algorithm, without regard for the impact 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 the user at the time of interest. The only filtering performed was to identify and exclude from the calculations any unhealthy SVs (those with subframe 1 health bits set to other than all 0's). 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.

Once the PDOPs had been computed across all grid points, for each of the 288 time increments during the day, the percentage of time the PDOP was ≤ 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 the PDOP is ≤ 6 was computed.

Table 3.4 summarizes the results of this analysis for the configurations all SVs available. The first column ("Average daily % over 2013") duplicates the values shown in Section 2. 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 2013.

Table 3.4: Summary of PDOP Availability

Metric	Average daily % over 2013	Minimum daily % over 2013
$\geq$ 98% Global Average PDOP ≤ 6	$\geq$ 99.999	99.998
$\geq$ 88% Worst site PDOP ≤ 6	99.991	98.611

In addition to verifying the standard, 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 the section describes those analyses and results.

3.5.2 Additional DOP Analysis

There are several ways to look at Dilution of Precision (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 3.5.1.

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

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

This represents a measure of the worst DOP performance. It is not particularly useful from the user's point of view since the location of the worst site varies throughout the day. However, it can be useful to the operators of the constellation when examining alternate constellations or constellations with failures.

Finally, the absolute worst time-point in a day is given by taking the maximum of the individual DOP values for all locations and all times.

$$DOP_{abs.\,worst}(day) = \max_{\lambda,\theta,t} (DOP_{\lambda,\theta,t})$$

Given that the $\langle DOP \rangle_{worst\,site}(day)$ is most closely related to the worse site definition used in Section 3.5.1, this is the statistic that will be used for "worst site" in the remainder of this section. For 2013, both $\langle DOP \rangle_{worst\,site}(day)$ and $\langle DOP_{worst\,site} \rangle(day)$ satisfy the SPS PS assertions, so the choice is not critical with respect to 2013.

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

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

This serves as a sanity check on the DOP results in general, and establishes that these metrics are increasingly sensitive to outliers.

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 globally average DOP and the $\langle DOP \rangle_{worst\,site}$ values. These values are presented in Table 3.5, with values for 2010 through 2012 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 3.5 are the annual means of the global average number of satellites visible to grid cells on a 111 km x 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 HDOP is the same as the worst site with respect to PDOP. For all quantities shown in Table 3.5 the values are very similar across all four years.

Table 3.5: Additional DOP Annually-Averaged Visibility Statistics for 2010 through 2013.

	$\langle DOP \rangle$				$\langle DOP \rangle_{worstsite}$			
	2013	2012	2011	2010	2013	2012	2011	2010
Horizontal DOP	0.83	0.84	0.85	0.86	0.96	0.96	0.98	0.98
Vertical DOP	1.35	1.36	1.38	1.39	1.69	1.69	1.72	1.74
Time DOP	0.78	0.79	0.81	0.81	0.91	0.91	0.93	0.95
Position DOP	1.59	1.60	1.62	1.64	1.85	1.85	1.88	1.91
Geometry DOP	1.77	1.79	1.81	1.83	2.05	2.05	2.09	2.12
Number of visible SVs	10.71	10.44	10.24	10.24	5.65	5.94	5.63	5.50

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 3.6 presents these values.

Table 3.6: Additional PDOP Statistics.

	2013	2012	2011	2010
Percentage of Days with the $\langle PDOP \rangle \leq 6$	100	100	100	100
Percentage of Days with the $\langle PDOP \rangle$ at Worst Site ≤ 6	100	100	100	100
98^{th} Percentile of $\langle PDOP \rangle$	1.63	1.65	1.68	1.71
88^{th} Percentile of $\langle PDOP \rangle_{worst\,site}$	1.88	1.87	1.93	1.93

Table 3.6 shows that the average DOP values for 2013 are nearly identical to previous years.

Behind the statistics are the day-to-day variations. Figure 3.10 provides a time history of the four PDOP metrics considering all satellites for 2013. Four metrics are plotted.

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

$PDOP_{abs.\,worst}$ is most sensitive to outliers and has features that are idiosyncratic to the particular events in a year, such as SV outages. This is easily understood when it is recognized that this is the only quantity that does not include averaging.

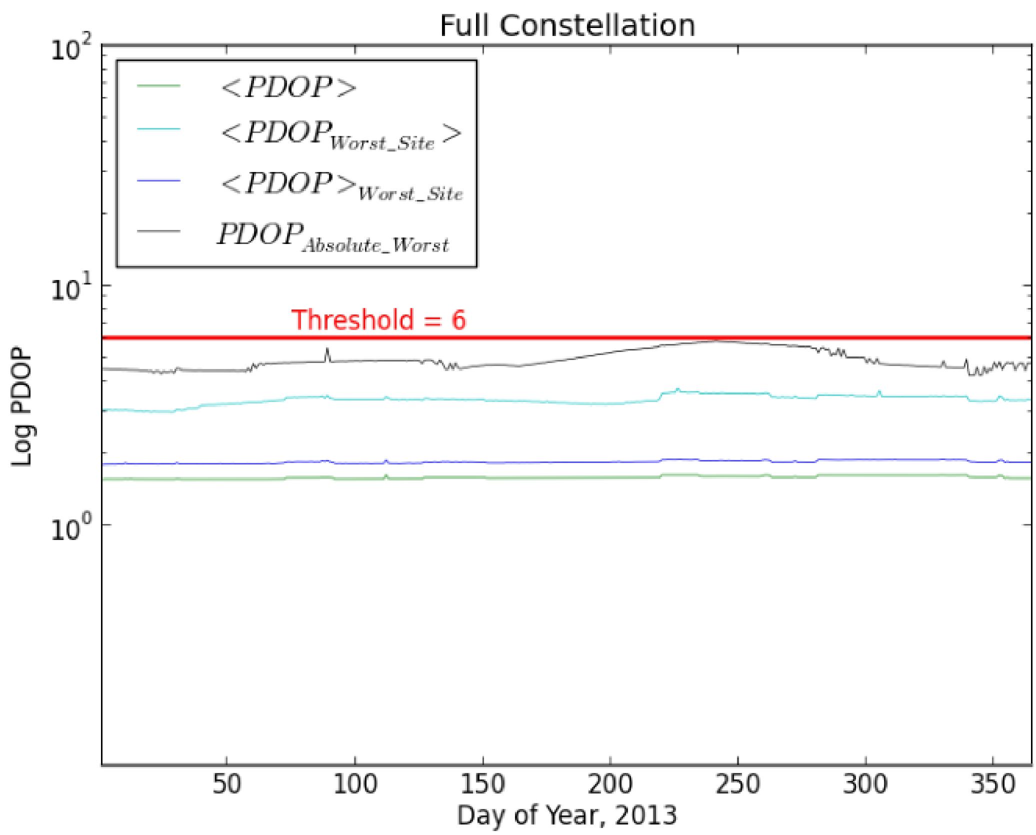


Figure 3.10: Daily PDOP Metrics Using all SVs, 2013

3.5.3 Position Service Availability

The positioning and timing availability standards are stated in Table 3.8-2 of SPSPS08 as follows:

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

The Conditions and Constraints associated with the standards include the specification of a 17 m horizontal 95% threshold and a 37 m vertical 95% threshold.

These are derived values as described in the sentence preceding SPSPS08 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."

Since the commitments for PDOP and constellation SPS SIS URE have not only been met, but exceeded, this assertion in the SPSPS08 implies that the position and timing availability standards must also be fulfilled. A direct assessment of these metrics was not undertaken.

3.5.4 Position Accuracy

The positioning accuracy standards are stated in Table 3.8-3 of SPSPS08 as follows:

- $\leq$ 9 m 95% Horizontal Error Global Average Position Domain Accuracy,
- $\leq$ 15 m 95% Vertical Error Global Average Position Domain Accuracy,
- $\leq$ 17 m 95% Horizontal Error Worst Site Position Domain Accuracy, and
- $\leq$ 37 m 95% Vertical Error Worst Site Position Domain Accuracy.

These are derived values as described in the sentence preceding SPSPS08 Table 3.8-3.

> "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 3.8-3."

Since the commitments for PDOP and constellation SPS SIS URE have been met and exceeded, then the position and timing accuracy standards would also be fulfilled.

While this answer is technically correct, it is not very helpful. Position accuracy is the primary reason that GPS exists. At the same time, position accuracy is a particularly difficult metric to evaluate due to the fact that GPS provides the SIS, but the user is responsible for appropriately processing the SIS to derive a position.

Section 2.4.5 of SPSPS08 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. For example,

> 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 SPSPS08 explains that in addition to the error exclusions listed in 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 satellite 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 [9] 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).

This list presents some challenges for any attempt to empirically verify the position accuracy metrics from real-world data. ARL:UT 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 and a similar set of 11 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. Therefore the first order tropospheric effects can be eliminated.
   (c) The receiver thermal noise will not be eliminated, but both the NGA and IGS stations are generally using the best available equipment and the thermal stability is routinely monitored, so effects will be limited.
   (d) Similarly, multipath cannot be eliminated, but both networks use antennas designed for multipath reduction, and station sites are chosen to avoid the introduction of extraneous multipath.
   (e) Antenna phase center locations for such stations are very well known. Therefore, position truth is readily available.
2. Process the data using a comprehensive set of broadcast ephemerides that have been checked for consistency. The set of ephemerides used in the URE studies described in Section 3.1 of this report had already been extensively tested and examined. They constitute a complete (or very nearly complete) set of the broadcast ephemeris available for 2013.
3. Process the collected observations using the PRSOLVE program of the ARL:UT-hosted open source GPS Toolkit (GPSTk)[10].
   (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, and WGS 84 conventions are used. Data from unhealthy SVs was 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 IGS data are 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 simple 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: 6.5 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.

The process departs from the SPS PS in that the minimum elevation angle for the analysis has been set to 10°. In our experience, data below 10° are far more likely to contain artifacts not related to the SIS. Examples of such effects include multipath and receiver behaviors associated with acquisition and loss of the signal. The latter in particular can produce erroneous pseudoranges that will be filtered from a RAIM solution, but will corrupt the autonomous pseudorange solution. This departure would be a significant concern if this analysis were intended as a verification of the standard. However, as discussed below, this is a empirical corroboration that verifies the standard has been met by meeting the PDOP and SPS SIS URE standards. In the future we will look more closely at extending our analysis to include the between 5 and 10 degrees, and the additional data quality checks we believe that will require.

This process yields four sets of results organized as detailed in Table 3.7.

Table 3.7: Organization of Positioning Results

Case	Constellation Considered	Data Editing Option	Data Source
1	All in View	RAIM	IGS Data
2			NGA Data
3		None	IGS Data
4			NGA Data

Once the solutions are computed, two sets of statistics are developed. 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 a 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.

3.5.4.1 Results for Daily Average

Using the approach outlined above, position solutions were computed at each 30s 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 SINEX files. Truth locations for the NGA stations were taken from station locations defined as part of the latest WGS84 adjustment with corrections for station velocities applied.

Residuals between estimated locations and the truth locations were computed (using PRSOLVE options) in the form of North, East and Up components in meters. The horizontal residual was computed from 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. Figure 3.11 through Figure 3.14 show the daily average for the horizontal and vertical residuals corresponding to the options shown in Table 3.7.

The statistics associated with the processing are provided in Table 3.8 through Table 3.11. There is one table each for the mean, median, maximum, and standard deviation of the daily values across 2013. 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. This choice of precision is based on the fact that the truth station positions are known only at the few-centimeter level.

The following general observations may be drawn from the charts and the supporting statistics.

- Outliers - From Figure 3.12 it is clear that there are few outliers (points beyond the established thresholds). For this figure, the effect of any one 30s outlier is reduced by the averaging factor, which is roughly 10 stations * 2880 epochs per day, or close to 30,000. Thus the impact of a 1000 m residual on the daily average would only be 3.3 cm.

- Mean & Median values The means and medians of the position residuals given in Table 3.8 and Table 3.9 are nearly identical for NGA data sets, suggesting that if there are any 30s position residual outliers, they are few in number and not too large. However, the mean is noticeably larger than the median for the IGS data with no editing. This suggests that there are some large outliers in the position residuals for IGS data with no editing. This is consistent with Figure 3.12.

Table 3.8: Mean of Daily Average Position Errors for 2013

Quantity	Data Source	Position Residual Mean (m)	
		RAIM	No Editing
Horizontal	IGS Data	1.14	15.21
	NGA Data	1.08	1.09
Vertical	IGS Data	1.73	22.91
	NGA Data	1.47	1.48

Table 3.9: Median of Daily Average Position Errors for 2013

Quantity	Data Source	Position Residual Median (m)	
		RAIM	No Editing
Horizontal	IGS Data	1.13	1.13
	NGA Data	1.08	1.09
Vertical	IGS Data	1.72	1.73
	NGA Data	1.46	1.48

Table 3.10: Maximum of Daily Average Position Errors for 2013

Quantity	Data Source	Position Residual Maximum (m)	
		RAIM	No Editing
Horizontal	IGS Data	1.36	3015.41
	NGA Data	1.26	1.26
Vertical	IGS Data	2.09	4153.19
	NGA Data	1.73	1.74

Table 3.11: Standard Deviation of Daily Average Position Errors for 2013

Quantity	Data Source	Position Residual Std. Dev. (m)	
		RAIM	No Editing
Horizontal	IGS Data	0.05	189.85
	NGA Data	0.03	0.03
Vertical	IGS Data	0.09	281.93
	NGA Data	0.05	0.05

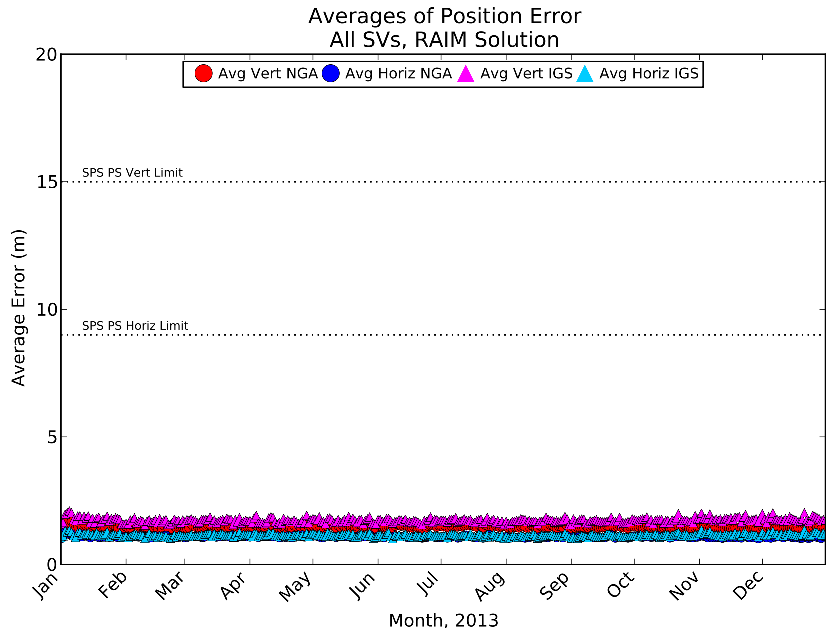


Figure 3.11: Daily averaged position residuals computed using a RAIM solution with default parameters.

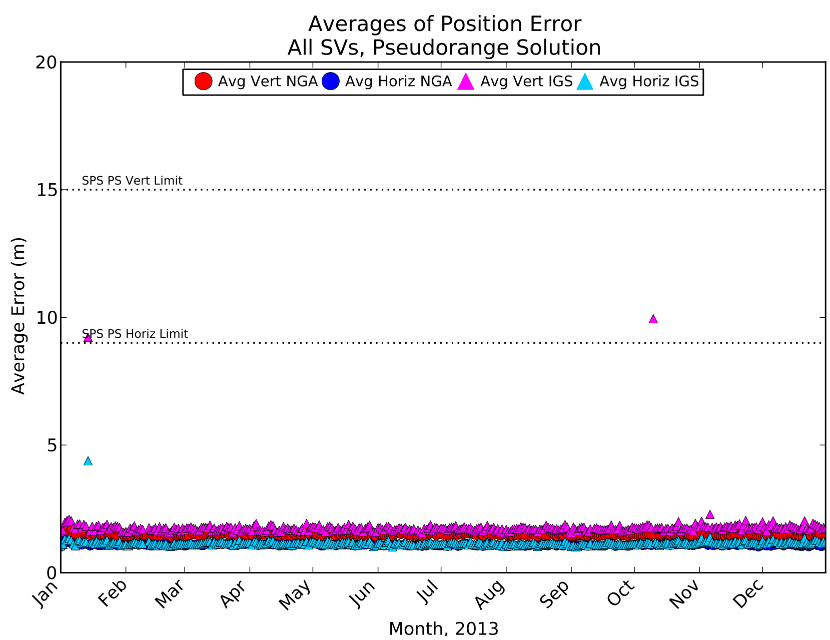


Figure 3.12: Daily averaged autonomous position residuals using no data editing.

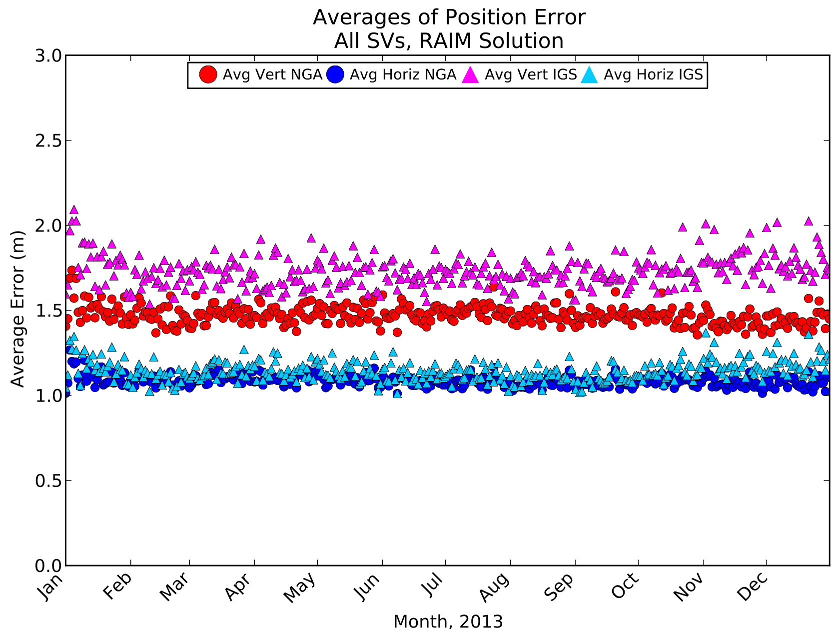


Figure 3.13: Pseudorange residuals for RAIM solution, enlarged to show variation in average residual. There is a clear distinction between the average vertical errors of the IGS stations and the NGA stations.

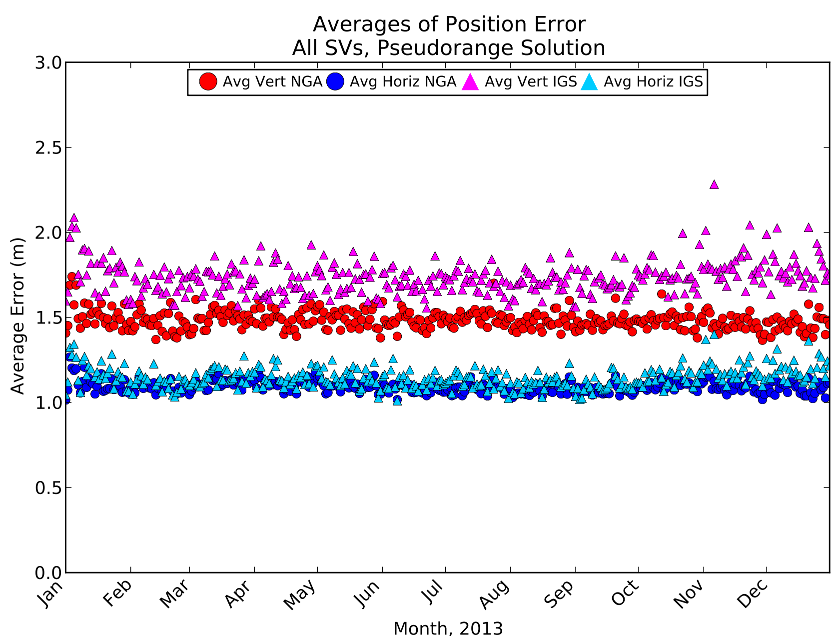


Figure 3.14: The non-edited pseudorange solution, enlarged to show variation in average residual.

- Network Difference Overall, the annual statistics presented in Table 3.8 through Table 3.11 point to the fact that the NGA data have smaller mean and median residuals, and a slightly tighter distribution as measured by the standard deviation.

- The average magnitude of the position residual reported in Table 3.9 is slightly smaller for the MSN stations then for the IGS stations. The horizontal means are very similar and the daily average values tend to overlap. There is more separation in the vertical values. This is a reversal of the trend in past years. The 2012 results indicated that IGS was lower than MSN throughout the year and the 2013 results indicate the reverse. Given some IGS stations had to be replaced in the 2013 analysis, it is likely that this difference is due to the different selection of IGS stations.

3.5.4.2 Results for Worst Site 95^{th} Percentile

The edited, and the non-edited, 30s position residuals were then processed (independently) to determine the worst site 95^{th} percentile values. In this case, the 95^{th} percentile was determined for each station in a given set, and the worst of these was used as the final 95^{th} percentile value for that day. Figure 3.15 and Figure 3.16 show these values for the various processing options described in the previous section. The plots are followed by tables of the statistics for the average, median, maximum, and standard deviation of the daily worst site 95^{th} percentile values. Some general observations on the results are included following the tables.

The statistics associated with the worst site 95^{th} percentile values are provided in Table 3.12 through Table 3.15. There is one table each for the average, median, maximum, and standard deviation of the daily values across 2013. As before, the results are organized in this fashion to facilitate comparison of the same quantity across the various processing options. Precisions are chosen to be at the cm level, a choice based on (a.) the magnitude of the standard deviation and (b.) the fact that the station positions are only known at the few-centimeter level.

Most of the observations from the daily averages hold true in the case of the results for the worst site 95^{th} percentile case. However, there are a few additional observations.

- Comparison between processing options - As before, the statistics for the RAIM solutions are effectively the same as the statistics for the autonomous pseudorange solutions. The worst value is the 6.86 m for the IGS vertical position maximum error, which is well within the 37 m 95% vertical error worst site requirement.

- Autonomous vs. RAIM - Comparing the autonomous and RAIM solutions it is clear that both are well within required limits. However, the average values presented are not a realistic representation of an individual user's experience and experience has shown that large outliers do occasionally occur as a result of the

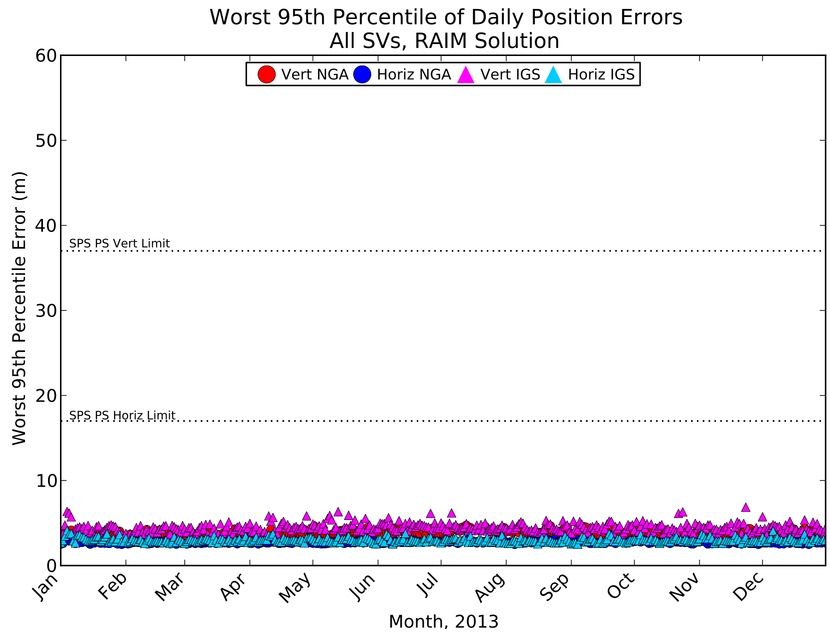


Figure 3.15: Worst site 95^{th} percentile horizontal and vertical residuals for the RAIM Solution. Note that vertical and horizontal limits are not violated.

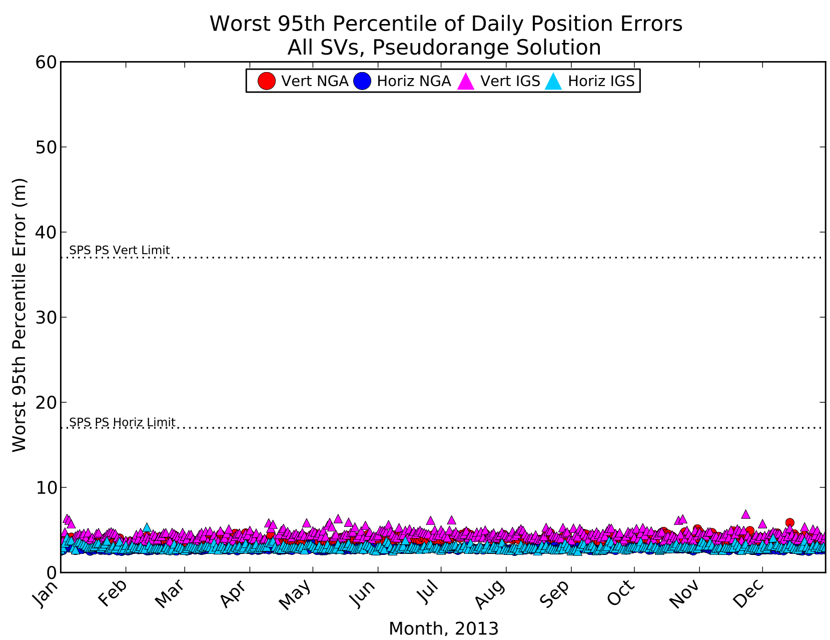


Figure 3.16: Worst site 95^{th} percentile horizontal and vertical residuals. All SVs available, pseudorange solution with no data editing. Note that vertical and horizontal limits are not violated.

receiver environment. A prudent measure is to implement some type of sanity checking on the input data.

- The values for average, median, and maximum of the worst 95^{th} percentile for both horizontal and vertical errors are well within SPS PS standard for both solutions. Compared to the SPS PS values of 17 m 95^{th} percentile horizontal and 37 m 95^{th} percentile vertical (for SPSPS08), these results are outstanding.

Table 3.12: Mean of Daily Worst Site 95^{th} Percentile Position Errors for 2013

Quantity	Data Source	Position Residual Mean (m)	
		RAIM	No Editing
Horizontal	IGS Data	2.99	3.00
	NGA Data	2.74	2.77
Vertical	IGS Data	4.45	4.45
	NGA Data	3.80	3.90

Table 3.13: Median of Daily Worst Site 95^{th} Percentile Position Errors for 2013

Quantity	Data Source	Position Residual Median (m)	
		RAIM	No Editing
Horizontal	IGS Data	2.93	2.94
	NGA Data	2.73	2.75
Vertical	IGS Data	4.39	4.39
	NGA Data	3.78	3.87

Table 3.14: Maximum of Daily Worst Site 95^{th} Percential Position Errors for 2013

Quantity	Data Source	Position Residual Maximum (m)	
		RAIM	No Editing
Horizontal	IGS Data	4.11	5.33
	NGA Data	3.18	3.59
Vertical	IGS Data	6.86	6.86
	NGA Data	4.73	5.85

Table 3.15: Standard Deviation of Daily Worst Site 95^{th} Percentile Position Errors for 2013

Quantity	Data Source	Position Residual Std. Dev. (m)	
		RAIM	No Editing
Horizontal	IGS Data	0.26	0.29
	NGA Data	0.12	0.15
Vertical	IGS Data	0.54	0.54
	NGA Data	0.35	0.40

Chapter 4

Additional Results of Interest

4.1 Frequency of Different SV Health States

The conditions under which various settings of navigation message health bits in subframe 1 will be used are described in Section 2.3.2 of SPSPS08. It appears that there are differences between the statements in SPSPS08 and actual practice.

SPSPS08 defines three SPS SIS health conditions in Section 2.3.2: Healthy, Marginal, and Unhealthy. The complete text of Section 2.3.2 is lengthy and will not be repeated here. However, the determination of Healthy, Marginal, or Unhealthy at a particular time is dependent on examination of four entities.

- SPS SIS Alarm Indications The alarm indicators are generally unavailable to a post-processing user as they require real-time information. For example, "The failure of parity of 5 successive words of NAV data", or "The broadcast IODE does not match the 8 LSBs of the broadcast IODC".
- The six-bit health status word from subframe 1 of the NAV message These values are available for each unique set of subframe 1, 2, 3 data.
- The URA alert flag A scan of the available navigation message data indicated no time in 2013 when the URA alert flag was raised on any SV. This might not be conclusive for some receivers since a change in the URA alert flag is not necessarily tied to a change in IODC/IODE. However, this study used navigation message data collected by the NGA MSN. The receiver used in the MSN during this period is the ITT Monitor Station Receiver (or the Ashtech Z(Y)-12 in the case of Tahiti). The conditions for output of a set of subframe 1, 2, 3 data from the Z(Y)-12 is a change in IODC/IODE or a change in the URA alert flag. The ITT receiver outputs all the navigation message data bits all the time and downstream software scans for changes in IODC/IODE or the URA alert flag.
- The SPS URA Index For Healthy and Marginal the URA is to be less than 8. No values greater than 7 were observed in 2013 (see Section 4.3).

Based on this description, the differentiation between states is (artificially) limited in this report to examination of the health bits in subframe 1.

- Healthy All six bits set to 0 (binary 000000_2).
- Marginal The MSB is set to 0_2 and the 5 LSBs are set to anything other than 00000_2 (all signals are OK), 00010_2 (all signals dead), or 11100_2 (SV is temporarily out).
- Unhealthy The MSB is set to 1_2 or the 5 LSBs are set to 00010_2 or 11100_2.

An additional note explains that the SPS SIS is unhealthy when the MSB is set to 1_2 and/or the 5 LSBs of the six-bit health status are set to 11111_2. It further notes "the Control Segment frequently uses this particular combination to indicate a 'dead' satellite."

Table 4.1 presents a summary of health bit usage in the ephemerides broadcast during 2013. Each row in the table presents a summary for a specific SV. The summary across all SVs are shown at the bottom. The table contains the count of number of times each unique health code was seen, the raw count of unique sets of subframe 1,2,3 collected during the year, and the percentage of sets of subframe 1,2,3 data that contained specific health codes.

Only two unique health settings were observed throughout 2013: binary 000000_2 (0x00) and binary 111111_2 (0x3F).

The health setting of 000000_2, given the other conditions noted earlier, corresponds to a SV status of Healthy. There were no occurrences of settings corresponding to the conditions for Marginal. Technically, there were no occurrences that correspond to basic SPSPS08 definition for Unhealthy. However, given the material in the notes, the occurrences of 111111_2 also count as Unhealthy.

4.2 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, 3 are available to the user to estimate the position of a SV. The accuracy of GPS (at least for users that depend on the broadcast ephemeris) is indirectly tied to the AOD since the prediction accuracy degrades over time (see Section 3.1.1). This is especially true for the clock prediction. It has been recognized that reducing the AOD improves PVT solutions for autonomous users; however, there is an impact in terms of increased operations tempo at 2^{nd} Space Operations Squadron.

The average AOD throughout 2013 is shown in the following table, along with values for the previous four years. The 2013 values for Block IIR, IIR-M and IIF SVs are nearly unchanged from 2012, while the average AOD for Block IIA SVs has recovered

Table 4.1: Frequency of Health Codes

SVN	PRN	Count by Health Code		Total # SF 1,2,3 Collected	Percent of Time by Health Code		Operational Days for 2013	Avg # SF 1,2,3 per Operational Day[a]
		0x3F	0x00		0x3F	0x00		
23	32	0	4757	4757	0.0	100.0	365	13.0
26	26	7	4746	4753	0.1	99.9	365	13.0
33	03	0	4892	4892	0.0	100.0	365	13.4
34	04	8	4749	4757	0.2	99.8	365	13.0
35	30	3	1286	1289	0.2	99.8	87	14.8
36	06	5	4770	4775	0.1	99.9	365	13.1
38	08	5	4928	4933	0.1	99.9	365	13.5
39	09	6	4910	4916	0.1	99.9	365	13.5
40	10	5	4858	4863	0.1	99.9	365	13.3
41	14	3	4753	4756	0.1	99.9	365	13.0
43	13	4	4750	4754	0.1	99.9	365	13.0
44	28	0	4793	4793	0.0	100.0	365	13.1
45	21	0	4761	4761	0.0	100.0	365	13.0
46	11	0	4759	4759	0.0	100.0	365	13.0
47	22	0	4785	4785	0.0	100.0	365	13.1
48	07	0	4754	4754	0.0	100.0	365	13.0
50	05	4	4756	4760	0.1	99.9	365	13.0
51	20	4	4751	4755	0.1	99.9	365	13.0
52	31	5	4757	4762	0.1	99.9	365	13.0
53	17	4	4751	4755	0.1	99.9	365	13.0
54	18	4	4757	4761	0.1	99.9	365	13.0
55	15	4	4752	4756	0.1	99.9	365	13.0
56	16	0	4757	4757	0.0	100.0	365	13.0
57	29	3	4759	4762	0.1	99.9	365	13.0
58	12	5	4753	4758	0.1	99.9	365	13.0
59	19	0	4757	4757	0.0	100.0	365	13.0
60	23	0	4754	4754	0.0	100.0	365	13.0
61	02	26	4743	4769	0.5	99.5	365	13.1
62	25	9	4749	4758	0.2	99.8	365	13.0
63	01	11	4742	4753	0.2	99.8	365	13.0
65	24	3	4808	4811	0.1	99.9	365	13.2
66	27	3	2525	2528	0.1	99.9	194	13.0
Total		131	147122	147253	0.1	99.9	365	403.4

[a] For further information on interpretation of these values, see the explanation below Figure 4.1

somewhat from a drop in 2012. The daily average AOD for the constellation and for each block is illustrated in the following figure. The AOD appears to be generally constant throughout 2013, which indicates that any variations in the URE results discussed earlier are not due to changes in operations tempo at 2SOPS.

Table 4.2: Age of Data of the Navigation Message by SV Type

	Average Age of Data (hours)					
	2008	2009	2010	2011	2012	2013
Full Constellation	11.5	11.7	11.6	11.6	11.3	11.5
Block II/IIA	11.1	11.5	11.5	11.4	10.3	10.9
Block IIR/IIR-M	11.7	11.8	11.8	11.7	11.7	11.8
Block IIF	-	-	12.2	12.0	11.5	11.5

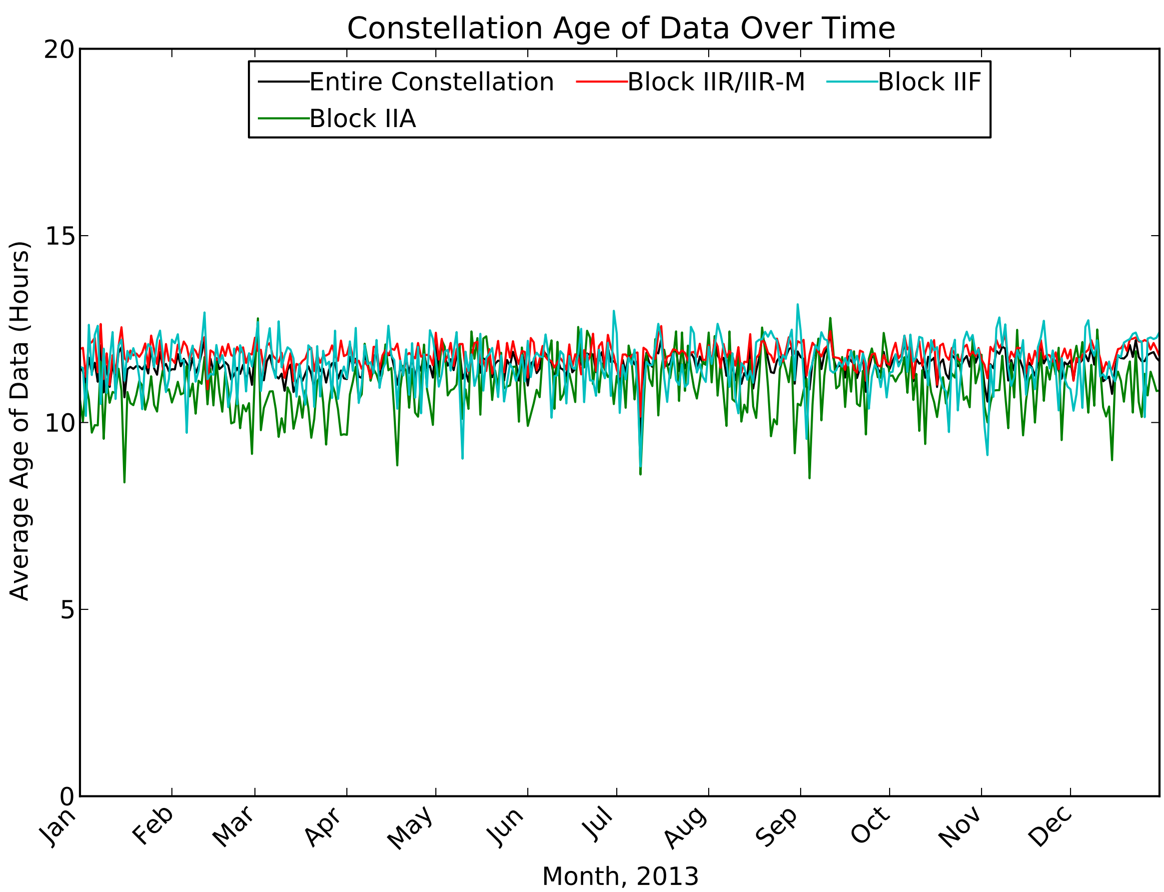


Figure 4.1: Constellation Age of Data for 2013

It is worth noting that the AOD for the Block II/IIA satellites is consistently slightly lower than that for the Block IIR/IIR-M and Block IIF satellites. This can be corroborated by reviewing the rightmost column on Table 4.1. This column shows the average number of unique sets of Subframe 1,2,3 data broadcast each day for each satellite. For the newer satellites, this value is typically 13.0 or 13.1. The number 13 comes about due to the fact that there would be 12 two-hour transmission periods in each day if one simply counts the number of two-hour periods in a day. However, when new navigation message data is uploaded, the cutover occurs within a two-hour interval, with the effect of adding a 13th unique set of navigation message data. Looking at the rightmost column of Table 4.1 to the lower SVN numbers, hence older satellites (e.g. SVN35), it can be seen that several of these satellites have slightly higher values for the average number of unique sets of Subframe 1,2,3 per day. These slightly higher values imply less time between uploads, and therefore slightly lower AOD values.

The AOD values (in both this section and in Section 3.1.1) were calculated by examination of the broadcast ephemeris and not by any information provided from the MCS. The method of calculation is described here both to allow other organizations to independently repeat this analysis.

The AOD calculations are based on the following assumptions.

- A complete set of the subframe 1, 2, 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.
- It is practical to find upload times based on the t_{oe} offsets as defined in IS-GPS-200 Section 20.3.4.5.

Given this set of assumptions, the AOD at any point in time can be determined by

- work backward from the time of interest to finding the time when the most recent preceding upload was first broadcast,
- find the AOD offset (AODO) of the associated subframe 2,
- subtract 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, and
- calculate 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 sufficiently large 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 2SOPS and are believed to be valid with one possible exception.

That exception concerns the AODO value. The original motivation for the AODO value was to provide timing information for the Navigation Message Correction Table (NMCT). The AODO is defined in IS-GPS-200 Section 20.3.3.4.1 para. 6. The application of the AODO is described in IS-GPS-200 Section 20.3.3.4.4. Both of these definitions are in relation to use of the AODO as part of the NMCT process. IS-GPS-200 is unclear whether the AODO parameter will be set as described in 20.3.3.4.1 and 20.3.3.4.4 if the NMCT is not provided in the broadcast navigation message. The fact that AODO is only defined and described in terms of its relationship to NMCT may indicate that a decision to turn off NMCT would result in an undetermined state for the AODO value. Underscoring this concern, this approach cannot be used for PRN 32. Since PRN 32 cannot have a valid NMCT (IS-GPS-200 20.3.3.5.1.9), the AODO term is not reset with an upload but is always set to the "all ones" condition.

This analysis indicates that there are uses for the AODO parameter beyond the original application to NMCT timing. Therefore, it would be useful to maintain the AODO parameter even if the NMCT is not computed and broadcast.

4.3 User Range Accuracy Index Trends

Tables 4.3 and 4.4 present a summary of the analysis of the URA index values throughout 2013. The total number of navigation messages examined differs from the health summary in Section 4.1 because only URA index values corresponding to health settings of 0x00 are included in this analysis. Both the absolute count and the count as a percentage of the total are shown.

The URA index values for SVN 35/PRN 30 are clearly different from the remainder of the constellation. This is unsurprising given the URE values presented earlier for SVN 35/PRN 30 (see Section 3.1.1).

If the values for SVN 35/PRN 30 are ignored, the vast majority of the values are 0, 1, or 2 (over 99.9%). Index values of 3 are very rare.

4.4 Extended Mode Operations

IS-GPS-200 defines Normal Operations as the period of time when subframe 1,2,3 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 SPSPS08 for the URE metrics. To determine if any SV operated in other than Normal Operations at any time in 2013, the broadcast ephemerides were examined to determine if any contained fit interval flags 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 48 examples of extended operations for satellites set healthy. The examples were distributed across 38 days. At least one example was found for each SV except for SVN 52, SVN 58, SVN 63, SVN 64, and SVN 66 for which there were no examples. The average time of an occurrence was 1 hour, 1 minutes. The

Table 4.3: Distribution of URA Index Values

SVN	PRN	URA Index								Total # SF 1,2,3 examined	Oper. Days for 2013	Avg # SF 1,2,3 per Oper. Day
		7	6	5	4	3	2	1	0			
23	32						3	310	4444	4757	365	13.0
26	26					1	8	337	4400	4746	365	13.0
33	03						238	1527	3127	4892	365	13.4
34	04						5	213	4531	4749	365	13.0
35	30	46	144	168	202	220	204	156	146	1286	87	14.8
36	06						155	999	3616	4770	365	13.1
38	08						127	1373	3428	4928	365	13.5
39	09						171	1465	3274	4910	365	13.5
40	10				5	1	194	1563	3095	4858	365	13.3
41	14				3	3	3	394	4350	4753	365	13.0
43	13				1	2	9	647	4091	4750	365	13.0
44	28						1	1022	3770	4793	365	13.1
45	21						2	82	4677	4761	365	13.0
46	11							376	4383	4759	365	13.0
47	22						255	1336	3194	4785	365	13.1
48	07						2	243	4509	4754	365	13.0
50	05							267	4489	4756	365	13.0
51	20						1	176	4574	4751	365	13.0
52	31						1	307	4449	4757	365	13.0
53	17					2	3	943	3803	4751	365	13.0
54	18			2	2	3	2	354	4394	4757	365	13.0
55	15							291	4461	4752	365	13.0
56	16						2	298	4457	4757	365	13.0
57	29				2	1	7	537	4212	4759	365	13.0
58	12							198	4555	4753	365	13.0
59	19							99	4658	4757	365	13.0
60	23							276	4478	4754	365	13.0
61	02							407	4336	4743	364	13.0
62	25						6	241	4502	4749	365	13.0
63	01							72	4670	4742	365	13.0
65	24						30	1105	3673	4808	365	13.2
66	27							273	2252	2525	194	13.0
Total		46	144	170	215	233	1429	17887	126998	147122	365	403.1

Table 4.4: Distribution of URA Index Values (As a Percentage of All Collected). Values smaller than 0.1 are not shown. Constellation averages are weighted by the number of observations.

SVN	PRN	URA Index							
		7	6	5	4	3	2	1	0
23	32						0.1	6.5	93.4
26	26					0.0	0.2	7.1	92.7
33	03						4.9	31.2	63.9
34	04						0.1	4.5	95.4
35	30	3.6	11.2	13.1	15.7	17.1	15.9	12.1	11.4
36	06						3.2	20.9	75.8
38	08						2.6	27.9	69.6
39	09						3.5	29.8	66.7
40	10				0.1	0.0	4.0	32.2	63.7
41	14				0.1	0.1	0.1	8.3	91.5
43	13				0.0	0.0	0.2	13.6	86.1
44	28						0.0	21.3	78.7
45	21						0.0	1.7	98.2
46	11							7.9	92.1
47	22						5.3	27.9	66.8
48	07						0.0	5.1	94.8
50	05							5.6	94.4
51	20						0.0	3.7	96.3
52	31						0.0	6.5	93.5
53	17					0.0	0.1	19.8	80.0
54	18			0.0	0.0	0.1	0.0	7.4	92.4
55	15							6.1	93.9
56	16						0.0	6.3	93.7
57	29				0.0	0.0	0.1	11.3	88.5
58	12							4.2	95.8
59	19							2.1	97.9
60	23							5.8	94.2
61	02							8.6	91.4
62	25						0.1	5.1	94.8
63	01							1.5	98.5
65	24						0.6	23.0	76.4
66	27							10.8	89.2
Constellation Average		0.0	0.1	0.1	0.1	0.2	1.0	12.2	86.3

minimum duration was 30 seconds and the maximum duration was 6 hours 11 minutes. These results are summarized in Table 4.5.

Given the relative rarity of occurrence, the URE values for the periods summarized in Table 4.5 are included in the statistics presented in Section 3.1.1, even though a strict interpretation of the SPSPS08 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 in order to reflect performance seen by the users.

Examination of the ephemerides from past years reveals that 2013 is not an anomaly. Such periods have been found in all years checked (back to 2005), however, the rate of occurance has been slowly declining and 2013 represents a new low.

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 4.5: Summary of Occurrences of Extended Mode Operations

SVN	PRN	# of Occurrences		Duration (minutes)	
		Healthy	Unhealthy	Healthy	Unhealthy
23	32	4	0	595	0
26	26	1	0	169	0
33	03	2	0	102	0
34	04	1	0	57	0
38	08	1	0	28	0
39	09	1	0	85	0
40	10	2	0	145	0
41	14	2	0	15	0
43	13	2	0	243	0
44	28	1	0	2	0
45	21	2	0	176	0
46	11	2	0	149	0
47	22	1	0	89	0
48	07	3	0	101	0
50	05	2	0	23	0
51	20	1	0	67	0
53	17	1	0	77	0
54	18	1	0	20	0
55	15	1	0	57	0
56	16	6	0	332	0
57	29	3	0	92	0
59	19	2	0	102	0
60	23	2	0	36	0
61	02	1	0	22	0
62	25	2	0	73	0
65	24	1	0	46	0
Totals		48	0	2903	0

Appendix A

URE as a Function of Age-of-Data

This appendix contains supporting information for the results presented in Section 3.1.2. The SIS RMS URE vs. AOD charts are presented for each GPS SV. The charts are organized by SV Block and by ascending SVN within each block.

These charts are based on the set of 30s Instantaneous RMS SIS URE values used in Section 3.1.1 were analyzed in a different manner. For each SV, a period of 48 hours was divided into a set of 192 bins, each 15 minutes in duration. An additional bin was added for any AOD that appeared beyond 48 hours. All of the 30s URE values for the year for a given SV were grouped according to AOD bin. The values in each bin were sorted and the 95^{th} Percentile and the maximum were determined. Once the analysis was complete, it was clear that most bins beyond the 26 hour mark contained too few points to be considered statistically relevant. Therefore, when the number of points in a bin falls below 10% of the number of points in most populated bin, the bin is not used for plotting purposes. The problem with bins with low counts is that, in our experience, the results tend to dominated by one or two very good or very bad observations and this can lead to erroneous conclusions about behavior.

The figures on the following pages each show two curves. The blue curve represents the 95^{th} Percentile SIS RMS URE vs. AOD (in hours). The green curve represents the number of data points that were available to form each URE estimate.

Note that for most SVs, the green 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 green 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 green curve will vary reflecting that difference.

A.1 Notes

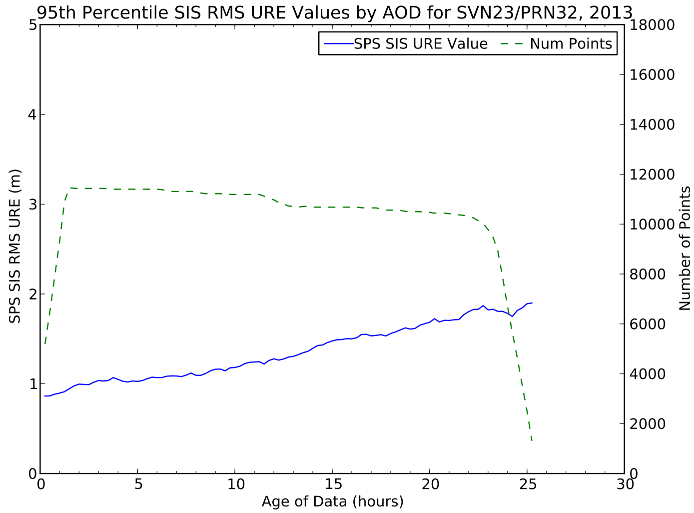
This section contains some notes on SV-specific behavior observed in the following charts.

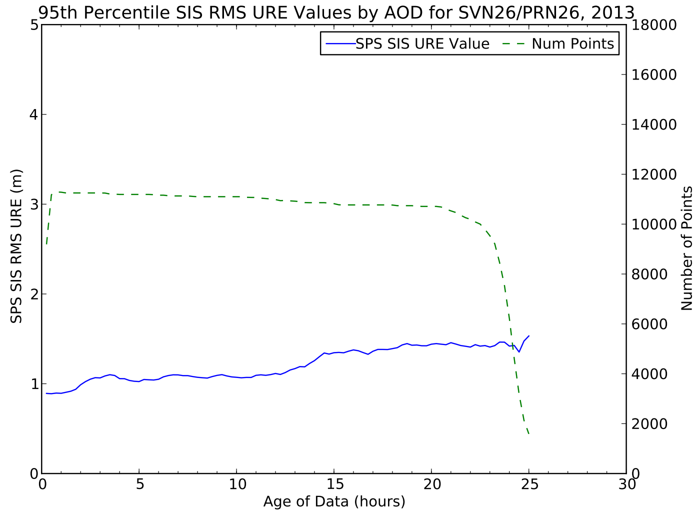
SVN 23/PRN 32: This SV presents a minor problem for this analysis. The AOD values are based on the AODO field in subframe 2. The definition of the AODO field is tied to how AODO is used to determine the age of the data in the navigation message correction table (NMCT). Since PRN 32 can never be represented in the NMCT, the AODO field for PRN 32 is never reset to zero at a new upload, but remains at the "all ones" state. Therefore, the AOD for PRN 32 cannot be independently derived from the navigation message data. For the purposes of this plot, we looked at the AODO across the entire constellation and determined the annual average AODO was about 5153 seconds ($\sim$ 1.4 hours). We then used this "representative" value as the AODO for SVN 23.

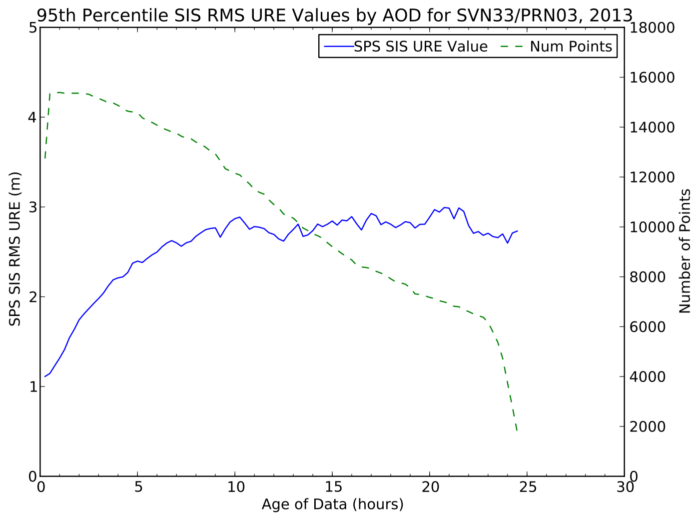
SVN 35/PRN 30: This is the most obvious example of a SV that is being uploaded more frequently than normal. The fact that it is being uploaded more frequently is based on the shape of the dashed green curve which indicates the number of points in each AOD bin. The scale for this curve is on the right-hand vertical axis. The green curve does not exhibit the plateau seen in most plots, but instead has a fairly rapid, near-linear decrease in number of points with AOD after about 2.5 hours. If the SV were consistently being uploaded at a given interval, there would still be a plateau, only shorter than the typical plateau. For example, if an SV were being uploaded every 12 hours, one would expect a plateau from somewhere around an hour AOD out to 12 hours AOD. The near linear trend implies that the upload time for this SV is variable over a fairly large range. Similar effects, but less pronounced, may be seen in the plots for several of the Block IIA SVs.

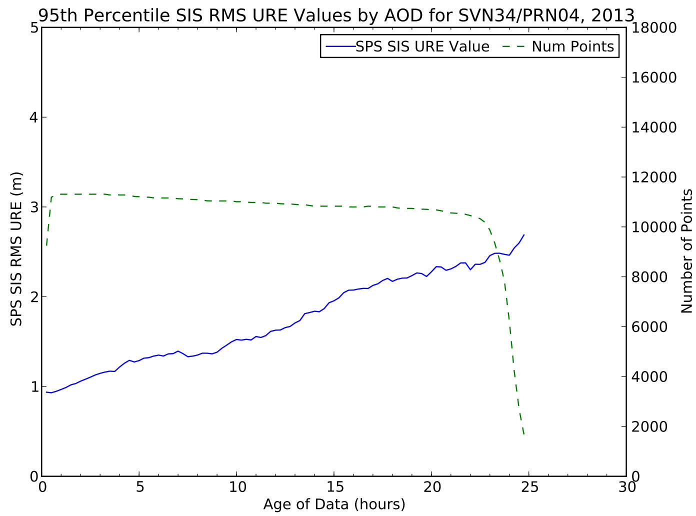
SVN 65/PRN 24: This Block IIF shows indications of occasional contingency uploads. This conclusion is based on the manner in which the SIS URE Value line tends to flatten as it approaches the 3 m magnitude and the fact that the number of points starts to decline far earlier than the other Block IIF SVs. This is consistent with the higher 95^{th}% URE shown in Table 3.1 and Figure 3.1. It is likely related to the fact that SVN 65/PRN 24 is the only Block IIF that is using a Cesium reference frequency.

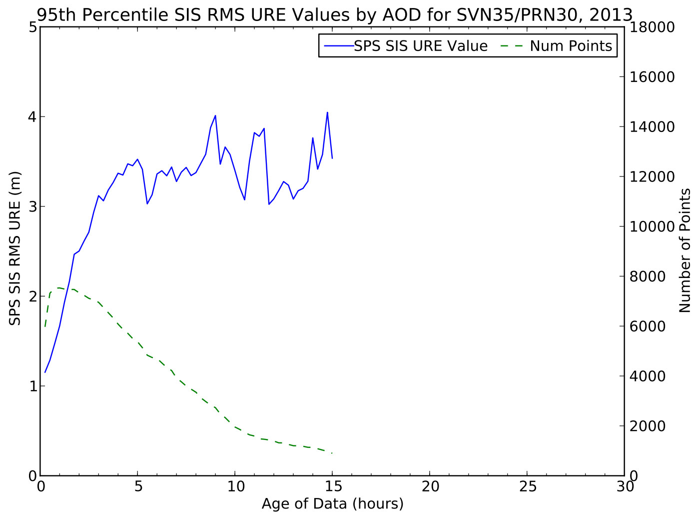
A.2 Block IIA SVs

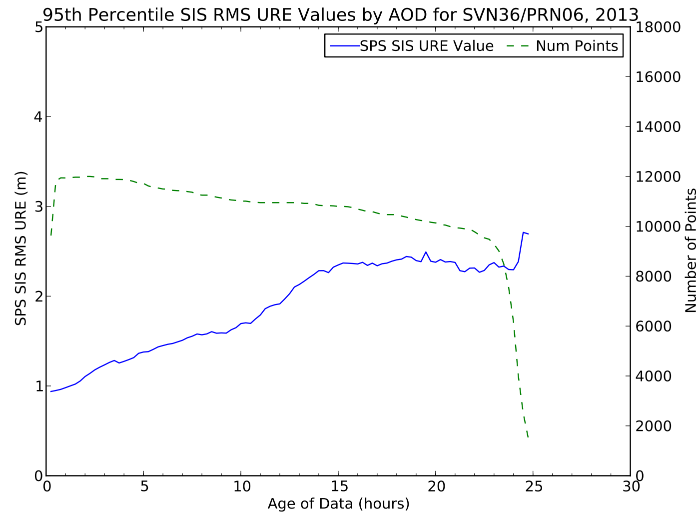


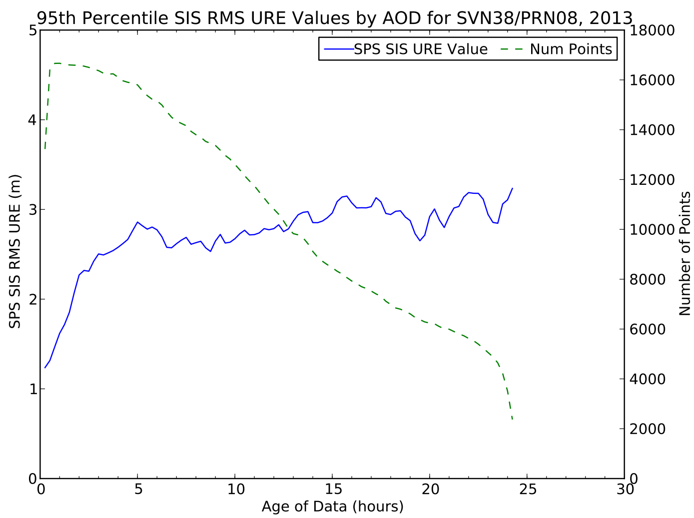


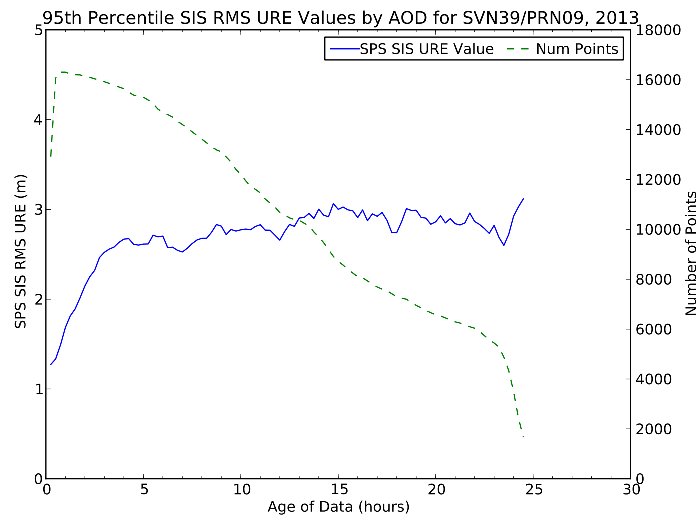


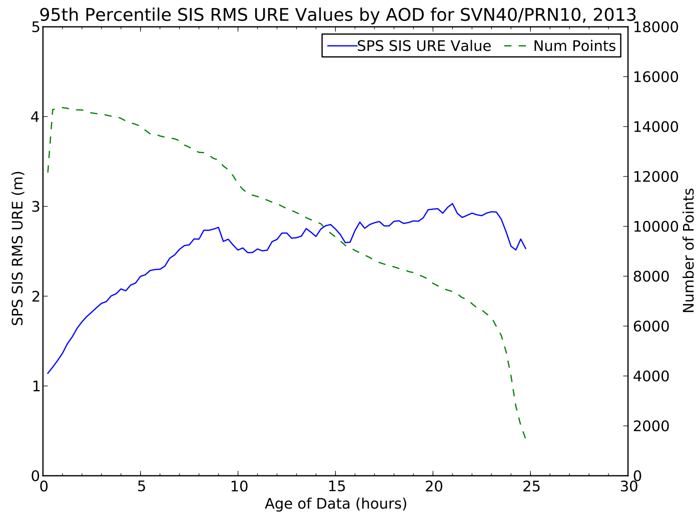



95th Percentile SIS RMS URE Values by AOD for SVN35/PRN30, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

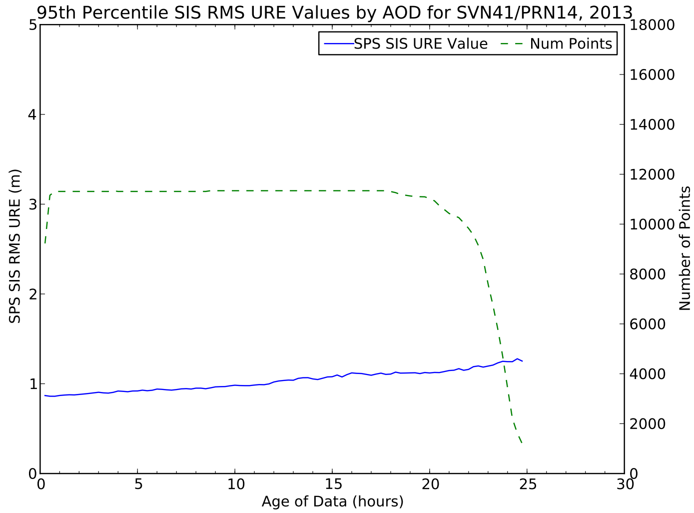

95th Percentile SIS RMS URE Values by AOD for SVN36/PRN06, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

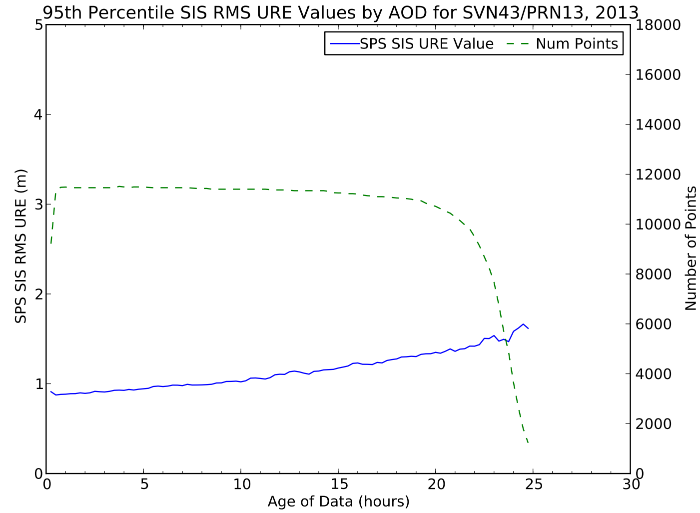

95th Percentile SIS RMS URE Values by AOD for SVN38/PRN08, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

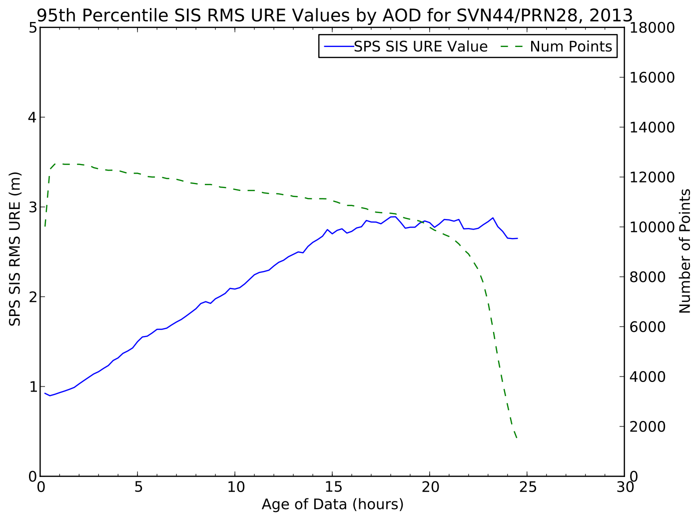

95th Percentile SIS RMS URE Values by AOD for SVN39/PRN09, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

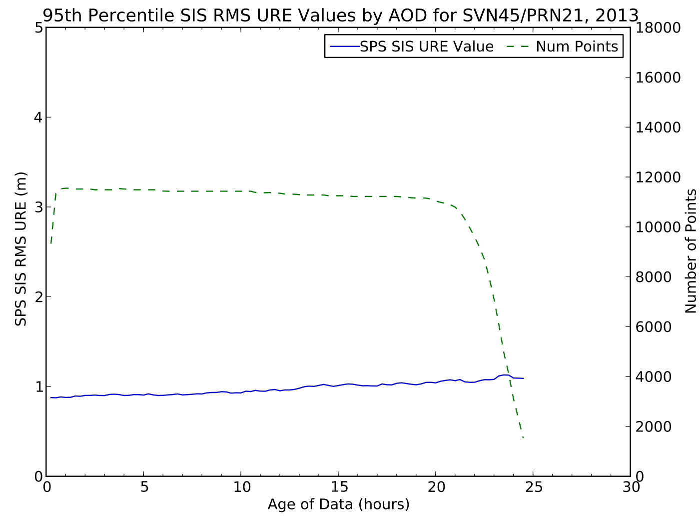

95th Percentile SIS RMS URE Values by AOD for SVN40/PRN10, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)
0
1
2
3
4
5
5
10
15
20
25
30
2000
4000
6000
8000
10000
12000
14000
16000
18000

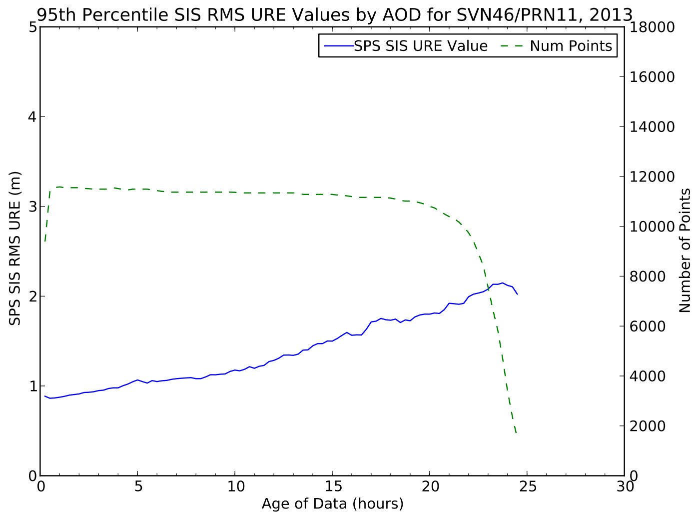
A.3 Block IIR SVs

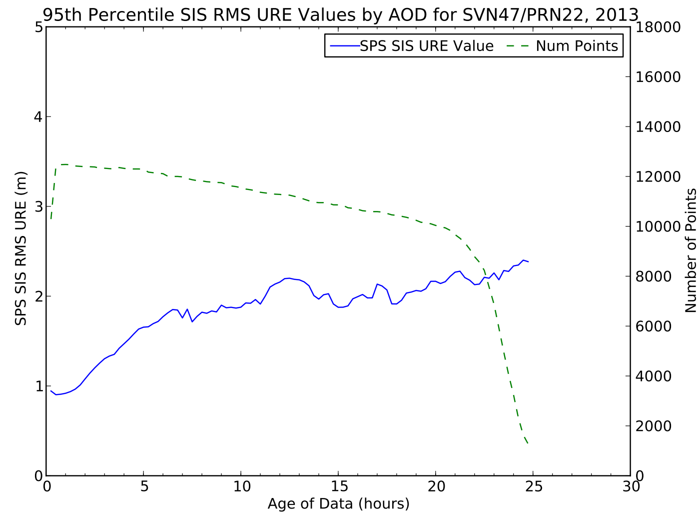


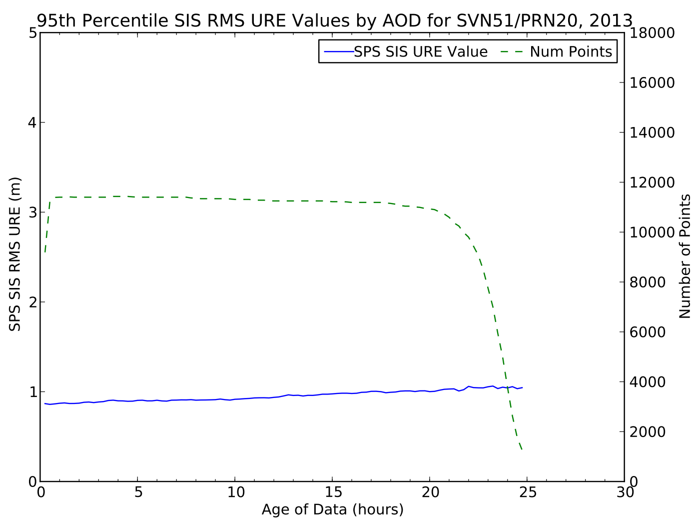


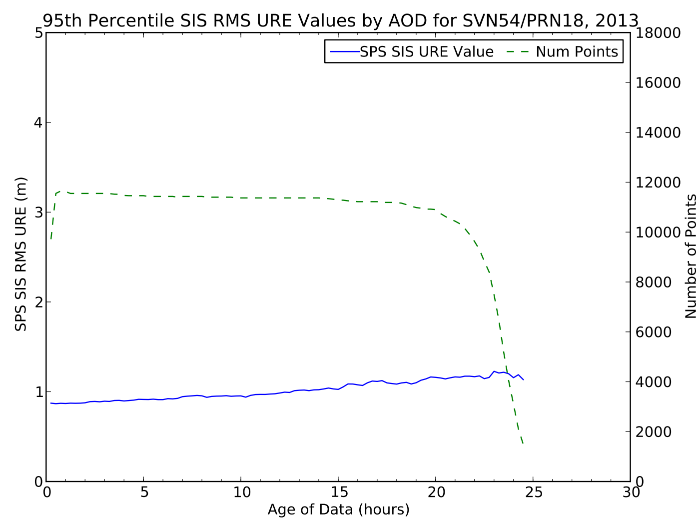


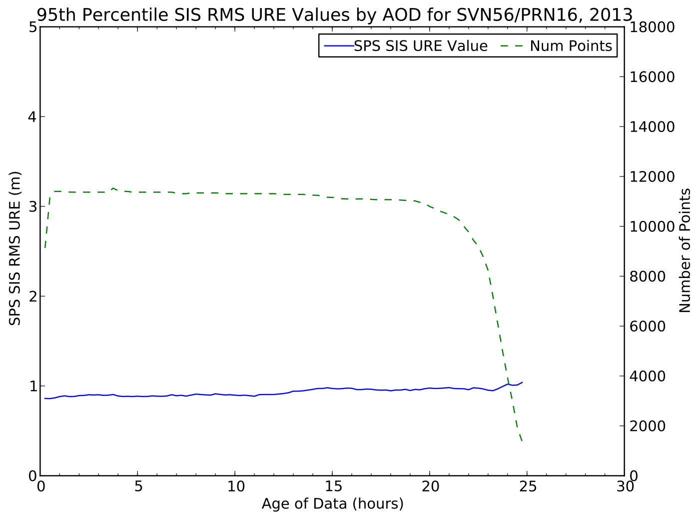


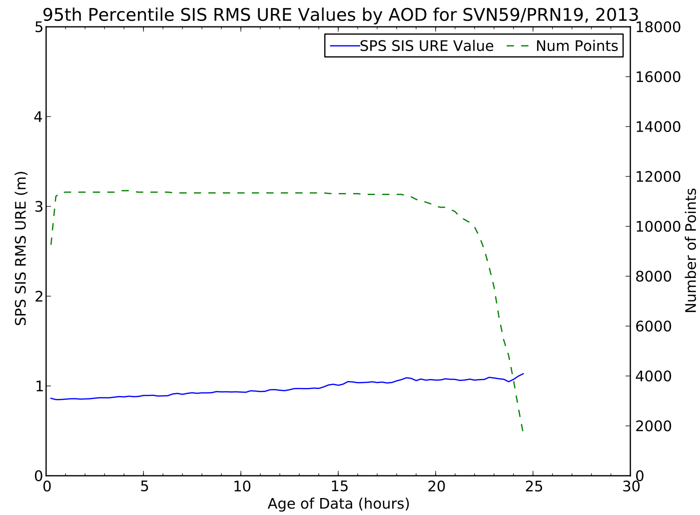

95th Percentile SIS RMS URE Values by AOD for SVN46/PRN11, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

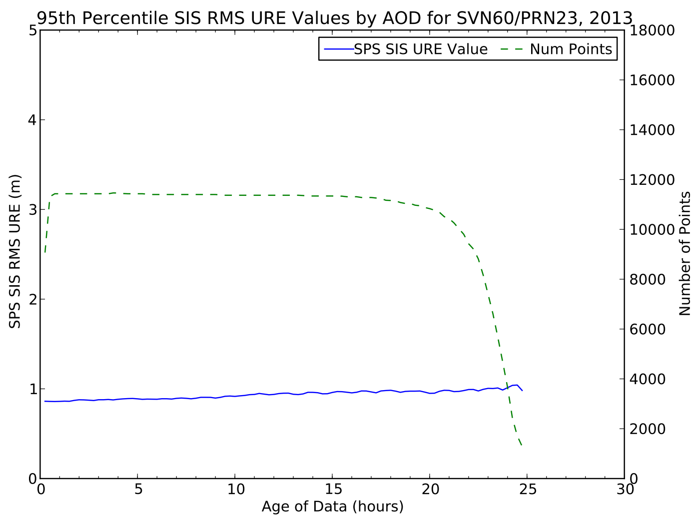

95th Percentile SIS RMS URE Values by AOD for SVN47/PRN22, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

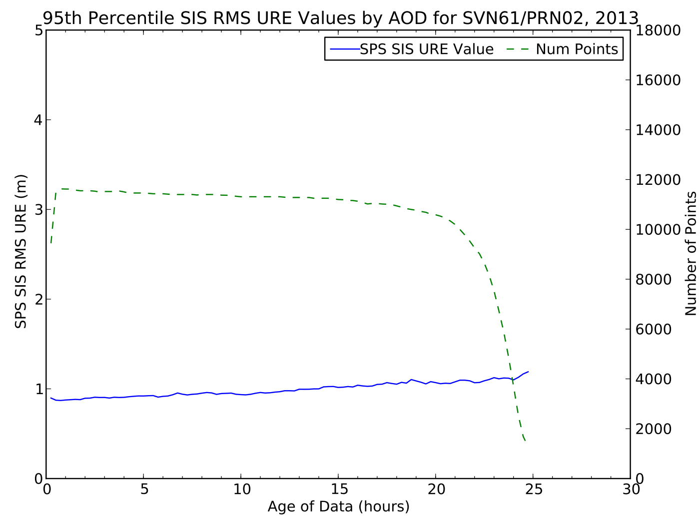

95th Percentile SIS RMS URE Values by AOD for SVN51/PRN20, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)


95th Percentile SIS RMS URE Values by AOD for SVN54/PRN18, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

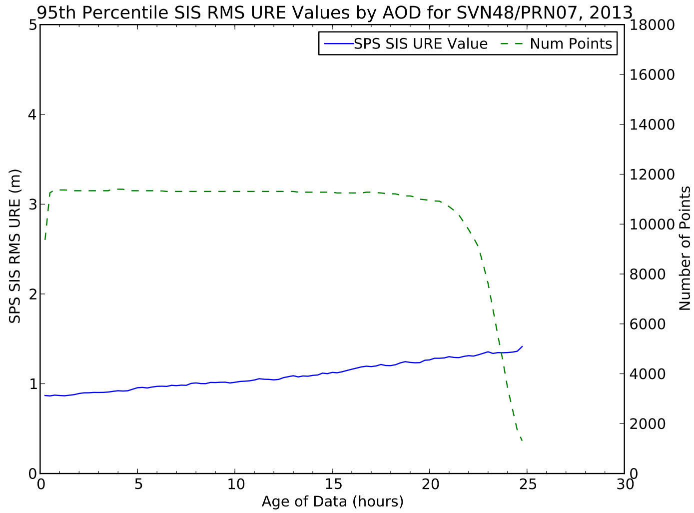

95th Percentile SIS RMS URE Values by AOD for SVN56/PRN16, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

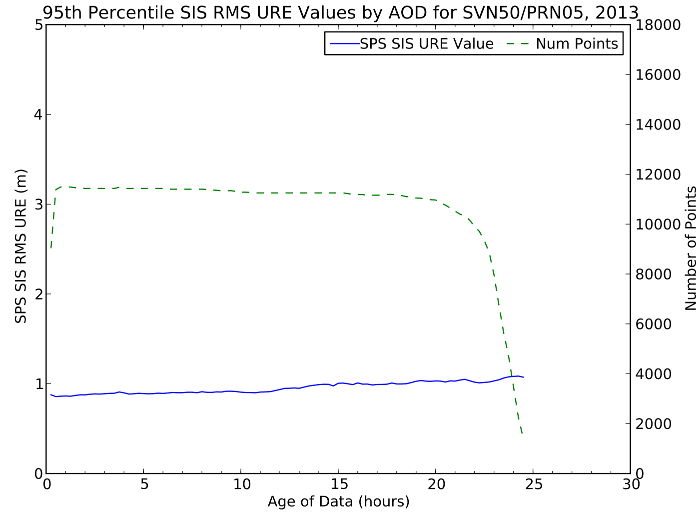

95th Percentile SIS RMS URE Values by AOD for SVN59/PRN19, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

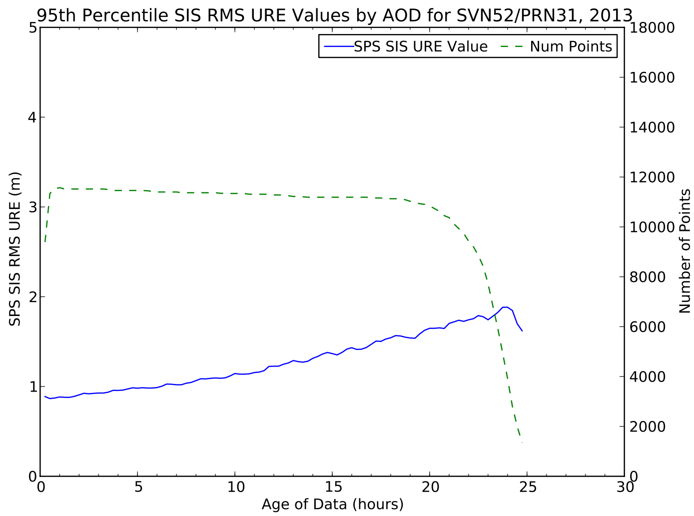

95th Percentile SIS RMS URE Values by AOD for SVN60/PRN23, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

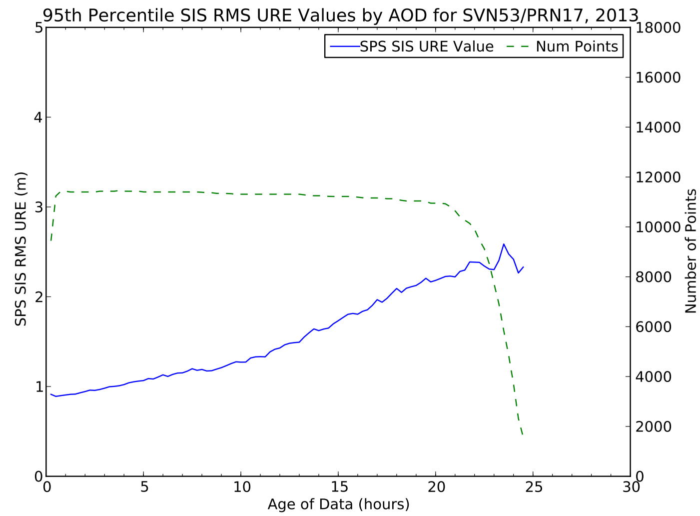

95th Percentile SIS RMS URE Values by AOD for SVN61/PRN02, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

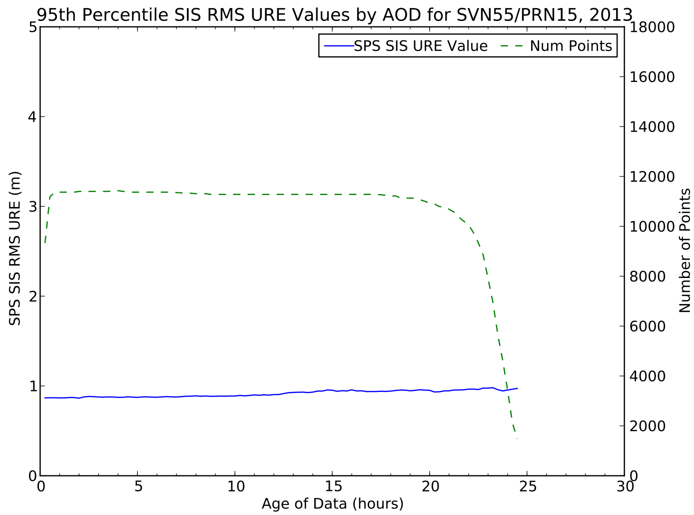
A.4 Block IIR-M SVs

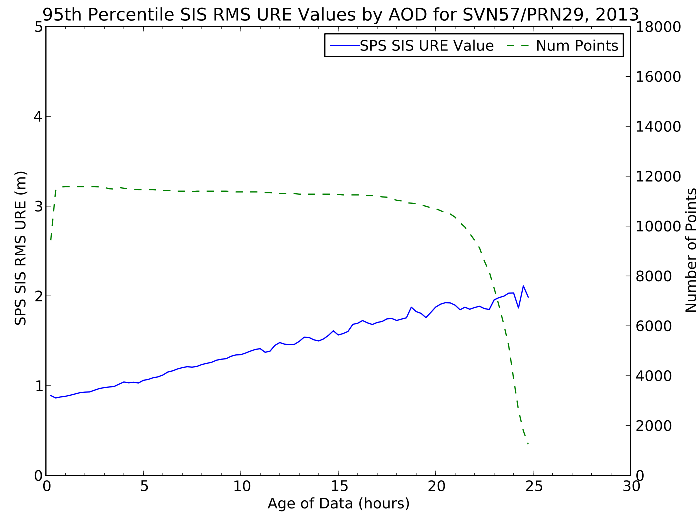


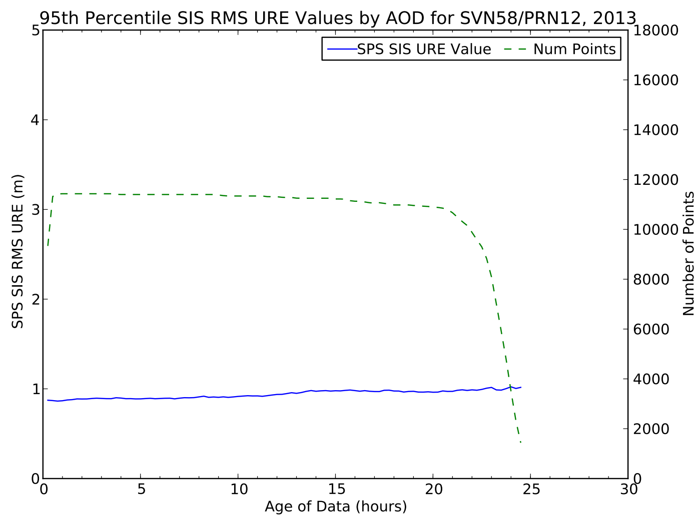




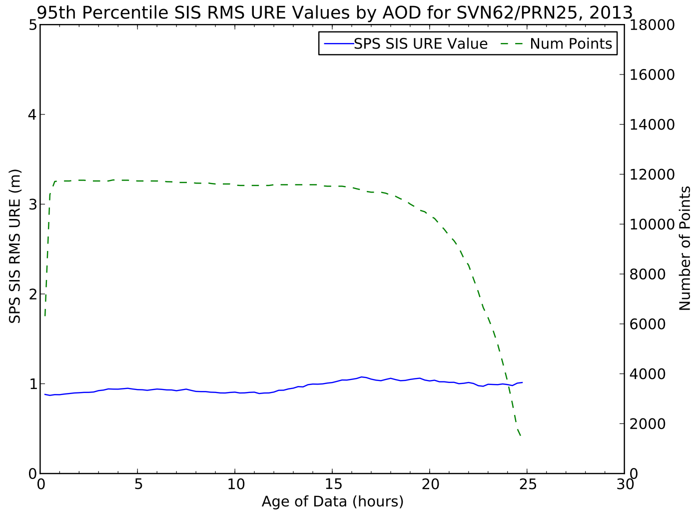


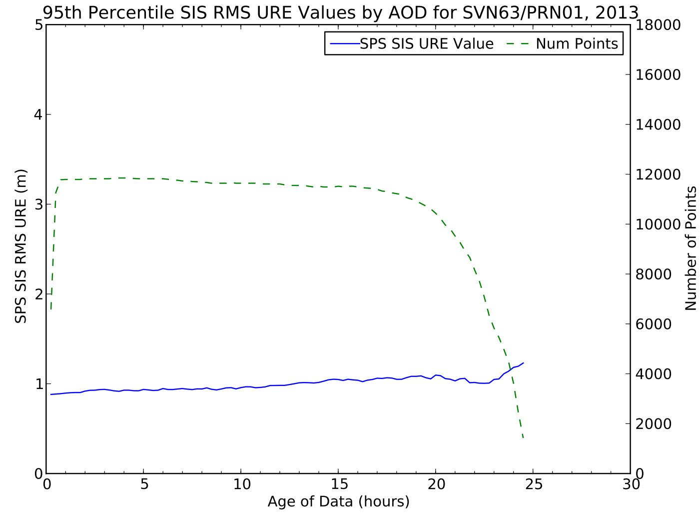

95th Percentile SIS RMS URE Values by AOD for SVN55/PRN15, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

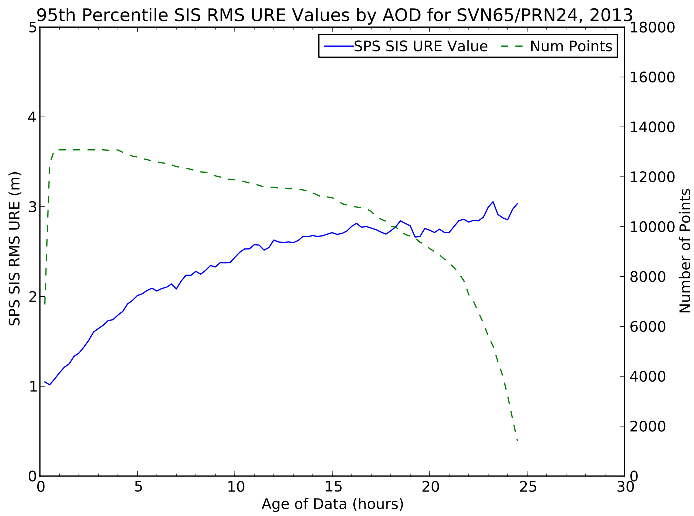

95th Percentile SIS RMS URE Values by AOD for SVN57/PRN29, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

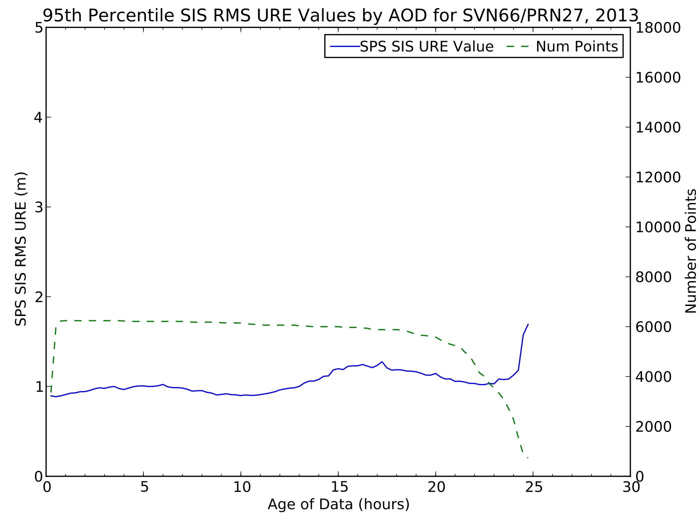

95th Percentile SIS RMS URE Values by AOD for SVN58/PRN12, 2013
SPS SIS URE Value
Num Points
SPS SIS RMS URE (m)
Number of Points
Age of Data (hours)

A.5 Block IIF SVs









Appendix B

Limitations of URE Analysis

The User Range Error (URE) accuracy represents the accuracy of the broadcast navigation message. There are a number of error sources that impact the URE, including errors in broadcast ephemeris and timing errors. The SPSPS specifications for this quantity require averaging across the service volume visible to a GPS SV at any specific point in time. In order to accomplish this we adopt equation A-1 of SPSPS08 Section A.4.1.1, which provides an expression for the rms value of the URE across the service volume. We reproduce this equation here in order to describe our process and its limitations.

Let

- c = the speed of light
- T = timing error
- R = radial orbit error
- A = along track orbit error
- C = cross track orbit error

then

$$Global\,Average\,URE = \left[(c\,T)^2 + (0.98\,R)^2 + (0.141\,A)^2 + (0.141\,C)^2 - 1.960\,c\,T\,R\right]^{\frac{1}{2}}$$

This expression allows us to compute the URE accuracy from known errors. To compute the known errors, we use the NGA precise ephemeris, which is based on dual-frequency P(Y)-code observations, as the "truth" estimate of SV position and clock, and we determine the quantities R,A,C and T, by differencing the precise ephemeris estimate of SV position and time with the broadcast ephemeris estimate of SV position and time.

For the purposes of this report, the Instantaneous RMS SIS URE values were generated at 30 second intervals for all of 2013. The NGA MSN was the source for the broadcast ephemerides used in this calculation. The NGA precise ephemerides were the source of the truth data. After all 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 and the maximum and the 95^{th} percentile values identified for each SV and this is the basis for Table 3.1.

There are a number of subtleties in this approach to computing URE accuracies, and the following paragraphs detail some of these.

Selective Availability would be an additional significant difference between PPS and SPS results; however, SA was set to zero throughout this period [11].)

The NGA precise ephemeris (PE) is provided in tabular SP3 format, with positions and clocks provided at a 5 minute cadence. The broadcast ephemeris (BE) is provided as a set of parameters for an equation which can be evaluated at any time for which the parameters are valid. Our process evaluates the BE at 30 second epochs (a spacing consistent with the RINEX data we use in other processing). So an evaluation of SV position and time from the NGA PE is required at each 30s epoch, and this requires interpolation to a 30s epoch test. The SV orbits are smooth, and so a Lagrange interpolation scheme is used, in which the five points prior to, and after, test are used to estimate the SV position. Clock interpolation is handled via a linear interpolation, since a multipoint Lagrange interpolation is not appropriate for clock dynamics.

This approach works well when the estimated URE accuracy is under 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 this procedure, without other cross-check mechanisms, can create some issues, and may lead to incorrect results. For example, in cases where an SV is removed from service for reasons that invalidate the broadcast ephemeris (such as a clock run-off) we need to compare the time at which the removal from service occurred with the time at which any of the URE accuracy bounds were exceeded in order to assess whether or not a violation of the SPS PS metrics occurred. However, because we have relied on the interpolation process to generate 30s values, we cannot obtain an accurate estimate of the time at which the URE bound was exceeded. As a general rule, the UREs computed in our process should be reviewed when they are contained between two SP3 epochs, one of which contains a clock event.

A more subtle problem lies in the fact that the behavior of the errors in such cases as the clock run-off is dependent on how the orbit analyst preparing the precise ephemeris chooses to address a clock discontinuity. Therefore, 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 choose to reconcile the analysis described above with the behavior of ORDs formed from the data collected at NGA and IGS sites. Since the observational data used is collected at a 30s cadence, we obtain a much higher resolution insight into the details of the actual event than we do with the interpolated PE.

Appendix C

SVN to PRN Mapping for 2013

Throughout the report, SVs have been referred to by both SVN and PRN. 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. As a result, the relationships have been changing several times throughout a year. Threfore it is useful to have a summary of the PRN to SVN mapping as a function of time. Figure C.1 presents that mapping for 2013. SVNs on the right vertical axis appear in the order in which they were assigned the PRN vlues in 2013. Start and end times of relationships are indicated by the dates along the upper horizontal axis. Note that several SVs were assigned PRN 30 suring 2013.

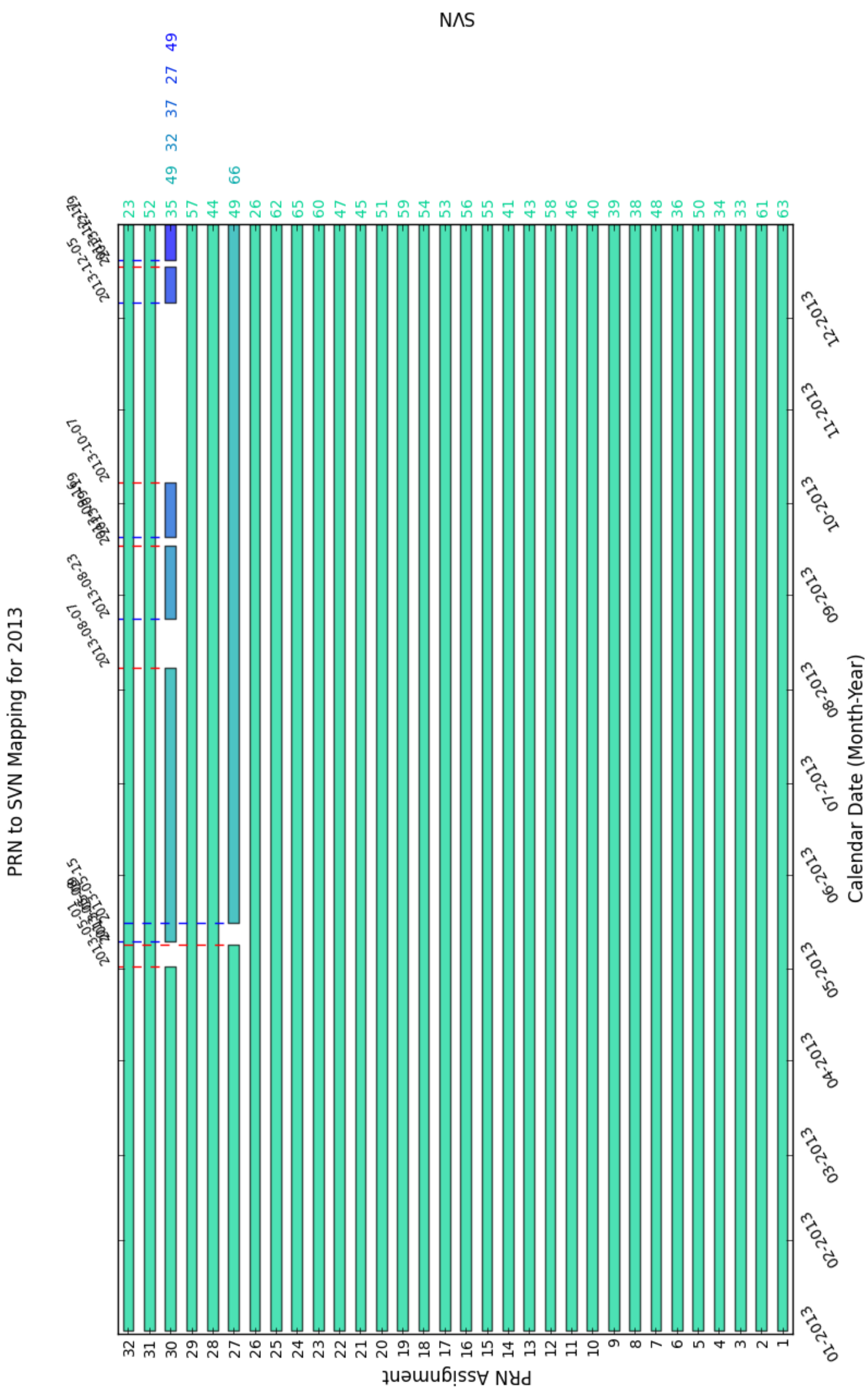


Figure C.1: PRN to SVN Mapping for 2013.

Appendix D

NANU Activity in 2013

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 D.1 presents a plot of the NANU activity in 2013. Green bars are scheduled outages and red bars represent unscheduled outages. Gray bars represent SVs that have been decommissioned. NANU numbers are indicated next to each bar. In the event that is more than on NANU for an outage, the earliest NANU nubmers is displayed.

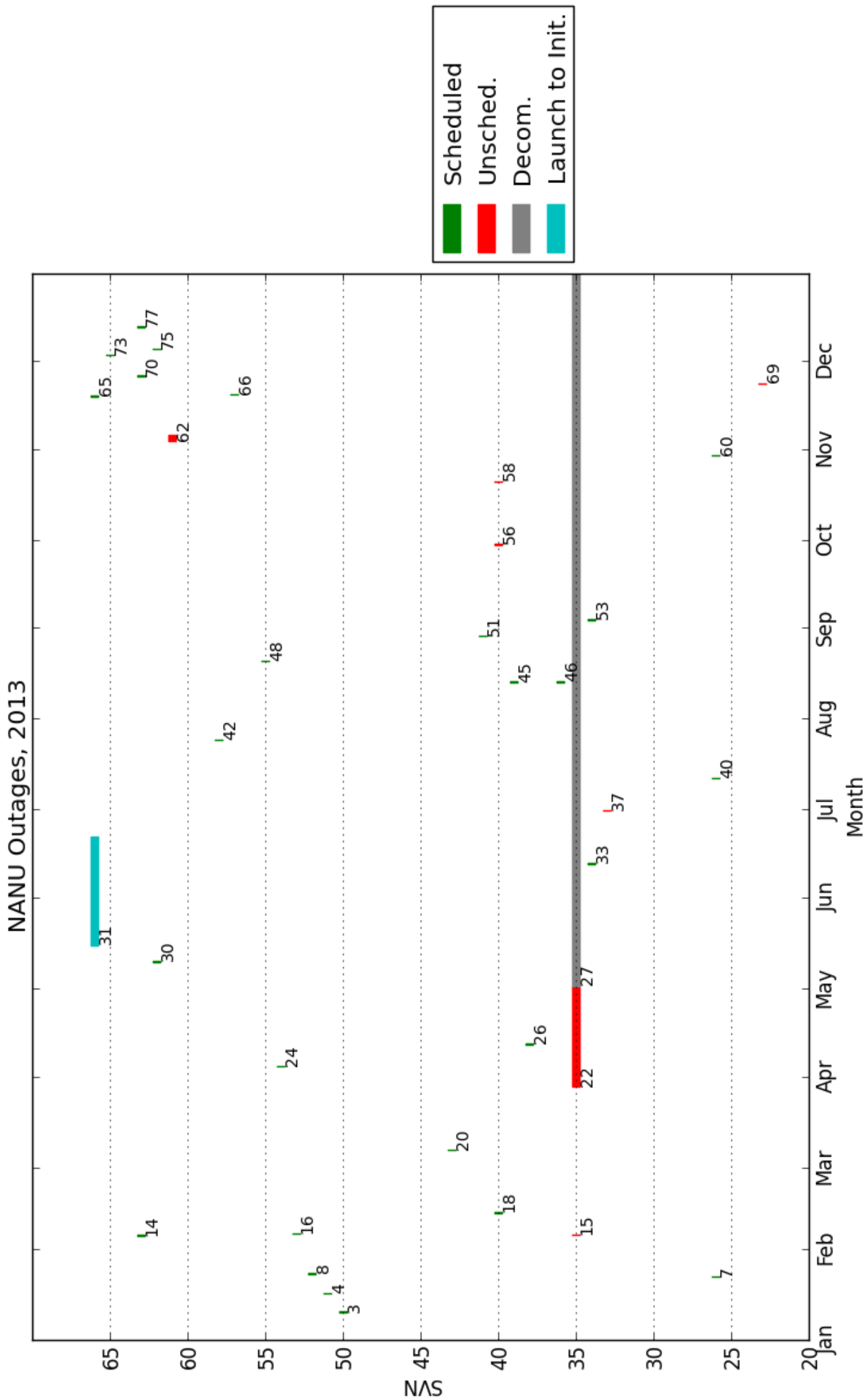


Figure D.1: Plot of NANU activity in 2013.

Appendix E

Translation of URE Statistics Between Signals

The URE process described in Appendix B is based on the data broadcast in Subframes 1, 2, 3 of the navigation message and the NGA precise ephemeris. Both of these estimates of the satellite orbits and clock offsets are referenced to the dual frequency P(Y)-code signal. Therefore, the URE results are directly related to the PPS Dual-Frequency performance. This appendix explains how these results have been interpreted in order to apply to the SPS assertions.

The PPS Dual-Frequency results may be mapped to SPS equivalent results by considering the effects of both the group delay differential and the intersignal bias (ISB) between the P(Y)-Code and the C/A-Code on L1.

E.1 Group Delay Differential

As described in IS-GPS-200 Section 3.3.1.7, the group delay through the satellite transmission hardware is accounted for in the satellite clock offset. However, there remains a group delay differential effect that comes about due to the fact that the signal passing through the different frequency chains experience slightly different delays. An estimate of the group delay differential is transmitted to the users in the navigation message using the T_{GD} term in Subframe 1. Note that T_{GD} is not the group delay differential, but the group delay differential scaled to account for the difference between a dual-frequency observation and a single-frequency observation. This is described in IS-GPS-200 Section 20.3.3.3.3.2. This distinction will be relevant below when comparisons to other estimates are discussed.

IS-GPS-200 Section 3.3.1.7.2 states that the random plus non-random variations about the mean of the differential delay shall not exceed 3.0 nsec (95% probability). While this establishes an upper bound on the uncertainty, it does not represent actual performance. The quantization in the T_{GD} term is 0.5 nsec. Therefore, even with perfect estimation, the floor on the uncertainty would be on the order of 0.25 nsec.

If one assumes that T_{GD} is correct and that the user equipment properly applies the correction, then the single-frequency results would be aligned with the dual-frequency results to within that quantization error. However, once the satellite is on orbit it is not possible to directly observe T_{GD}. Instead it must be estimated and the estimates are subject to a variety of factors including receiver group delay differential effects and ionospheric dispersion. This uncertainty has the effect of inflating the PPS Dual-Frequency results when these results are interpreted in terms of the PPS Single-Frequency or SPS services. In fact, since the errors are not directly observable, the best that can be done is to examine the repeatability in the estimate or the agreement between independent estimates and consider these as proxies for the actual uncertainty.

Since 1999, the T_{GD} values have been estimated by JPL and provided to 2 SOPS on a quarterly basis. Shortly before this process was instituted there was a study of the proposed estimation process and a comparison of the estimates to those independently developed by two other sources [12]. The day-to-day uncertainty in the JPL estimates appeared to be about 0.3 nsec and the RMS of the differences between the three processes (after removal of a bias) was between 0.2 nsec and 0.7 nsec.

Currently, the Center For Orbit Determination (CODE) at the University of Bern estimates the P1-P2 bias [13]. CODE provides a group delay differential estimate for each SV every month. CODE does not provide details on the estimation process, but it must include a constraint that the group differential delay averaged over the constellation is zero as all sets of monthly values for 2013 exhibit a zero mean.

A comparison of the CODE estimates and the T_{GD} values (scaled by to group differential delay values) shows a ∼5 nsec bias between the estimates. This bias may be removed as we are comparing mean-removed vs non-mean removed values. After the bias across the constellation is removed, the level of agreement between the scaled T_{GD} values and the monthly CODE estimates is between 0.1 nsec and 0.8 nsec RMS. (Note: Results for SVN 49 appear to be out-of-family and have been excluded in this comparison)

Considering all these factors, for the purpose of this analysis the uncertainty in the T_{GD} is assumed to be 0.5 nsec RMS.

E.2 Intersignal Bias

The ISB represents the difference between two signals on the same frequency. This bias is due to differences in the signal generation chain coupled with dispersive effects in the transmitter due to the differing bandwidths of the signals. It is not possible to observe these effects directly. When examining the signal structure at the nanosecond level the chip edges are not instantaneous transitions with perfectly vertical edges, but exhibit rise times that vary by signal. Therefore, measuring the biases requires assumptions about the levels at which one decides a transition is in progress. These assumptions will vary between receivers.

There is no estimate of the ISB provided in the GPS legacy navigation message. However, CODE estimates the bias between the L1 P(Y)-code and the L1 C/A-code [13]. An estimate is provided for each SV every month. These estimates were examined for each month in 2013. The monthly mean across all SVs is zero, indicating the estimation process is artificially enforcing a constraint. The RMS of the monthly values across the constellation is 1.2 nsec for each month. Since there is no estimate of the ISB, this RMS represents an estimate of the error C/A users experience due to the ISB.

E.3 Adjusting PPS Dual-Frequency Results for SPS

The PPS Dual-Frequency and SPS cases are based on a different combination and a different code. Therefore, the uncertainties in both T_{GD} and ISB must be considered. The PPS Dual-Frequency URE results are all stated as $95^{th}\%$ (2-sigma) values. This means that the RMS errors estimated in F.2 and F.3 must be multiplied by 1.96 (effectively 2, given that the amount of uncertainty in the values).

If it is assumed that these errors are uncorrelated, the total error may be estimated as

$$\begin{aligned} \text{Total error} &= \sqrt{((2 * \mathrm{T_{GD}}\ \text{uncertainty})^2 + (2 * \text{ISB uncertainty})^2)} \\ &= \sqrt{((2 * 0.5\text{nsec})^2 + (2 * 1.2\text{nsec})^2)} \\ &= \sqrt{(1\text{nsec}^2 + 5.76\text{nsec}^2)} \\ &= 2.6\text{nsec} \end{aligned} \tag{E.3.1}$$

Converted to equivalent range at the speed of light and given only a single significant digit is justified, the total error is about 0.8 m. This adjustment may then be combined with the PPS-Dual Frequency result in a root-sum-square manner.

Bibliography

[1] U.S. Department of Defense. Standard Positioning Service Performance Standard, 4th Edition, 2008.

[2] U.S. Department of Defense. Navstar GPS Space Segment/Navigation User Interfaces, IS-GPS-200, Revision G, September 2012.

[3] John M. Dow, R.E. Neilan, and C. Rizos. The International GNSS Service in a changing landscape of Global Navigation Satellite Systems. *Journal of Geodesy*, 2009.

[4] B. Renfro, D. Munton, and R. Mach. Around the World for 26 Years - A Brief History of the NGA Monitor Station Network. In *Proceedings of the Institute of Navigation International Technical Meeting*, Newport Beach, CA, 2012. Institute of Navigation.

[5] U.S.Naval Observatory. Block II Satellite Information. `ftp://tycho.usno.navy.mil/pub/gps/gpstd.txt`, January 2011.

[6] W. Gurtner and L. Estey. RINEX: The Receiver Independent Exchange Format Version 2.11, 2006.

[7] U.S. Department of Defense. Navstar GPS Control Segment to User Support Community Interfaces, ICD-GPS-240, Revision A, January 2010.

[8] U.S. Department of Transportation. Global Positiong System (GPS) Civil Monitoring Performance Specification, DOT-VNTSC-FAA-09-08, April 2009.

[9] NIMA Technical Report TR8350.2. Department of Defense World Geodetic System 1984, Its Definition and Relationships With Local Geodetic Systems, July 1997.

[10] B. Tolman et al. The GPS Toolkit - Open Source GPS Software. In *Proceedings of the 17th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2004)*, Long Beach, CA, 2004. Institute of Navigation.

[11] The White House, Office of the Press Secretary. Statement by the President Regarding the United States' Decision to Stop Degrading Global Positioning System Accuracy, May 2000.

[12] Colleen H. Yinger, William A. Feess, Ray Di Esposti, The Aerospace Corporation, Andy Chasko, Barbara Cosentino, Dave Syse, Holloman Air Force Base, Brian Wilson, Jet Propulsion Laboratory, Maj. Barbara Wheaton, and SMC/CZUT. GPS Satellite Interfrequency Biases, June 1999.

[13] Data Set for 2013. ftp://ftp.unibe.ch/aiub/CODE/2013, 2013.