Satellite Navigation Branch, ANG-E66

GALILEO OPEN SERVICE PERFORMANCE ANALYSIS REPORT

September 2024

Report #13
Reporting Period: October 1, 2023 to December 31, 2023
http://www.nstb.tc.faa.gov

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DOCUMENT VERSION CONTROL

VERSION	DESCRIPTION OF CHANGE	DATE
0.1	Initial Draft	06/05/2024
0.2	Internal Peer Review	06/21/2024
0.3	External Peer Review	08/30/2024
1.0	Final Report	09/23/2024

EXECUTIVE SUMMARY

In 2016, the European Union (EU) made available the Galileo Global Navigation Satellite System (GNSS) [1]. This system provides ranging, navigation, and timing services to properly equipped users. Galileo is currently in its initial operational capability phase. Galileo is a GNSS similar to the United States (U.S.) Global Positioning System (GPS). Galileo and GPS are interoperable and transmit signals on the same frequencies.

This report focuses exclusively on the Galileo performance. The Federal Aviation Administration (FAA) publishes a separate report on GPS performance and Advanced Receiver Autonomous Integrity Monitoring (ARAIM) performance. ARAIM is a dual-frequency/multi-constellation scheme that uses GPS and Galileo in an aviation application.

The Galileo performance assessment evaluates parameters in the Galileo Open Service (OS) Service Definition Document (SDD), version 1.2 [2]. The following parameters and high-level results for the quarter are included in this report or future reports. Although the new version 1.3 of the SDD was released in November 2023, version 1.2 was used for purposes of this report.

Availability of Galileo Position Dilution of Precision (PDOP). The availability of PDOP less than or equal to 6 is calculated on an equally spaced grid across the world as a monthly statistic to coincide with Minimum Performance Level (MPL) in the OS SDD. Using Galileo navigation data (ephemerides and satellite health) provided by the International GNSS Service (IGS), coverage data was calculated for each month in the reporting period. Availability of PDOP was greater than 99.5% for October, November, and December.

Signal Health and Accuracy F/NAV Signal-in-Space Accuracy (SISA). Using a Wide Area Augmentation System (WAAS) G-III receiver at the FAA William J. Hughes Technical Center (WJHTC) in Atlantic City, New Jersey, Galileo E5a F/NAV signals were tracked with the health assessed as per Figure 4 in the OS SDD v1.2 document [2]. The decoded F/NAV data from the NovAtel G-III receiver was examined along with any available Notices Advisory to Galileo Users (NAGUs) relevant to each non-healthy event. Section 3.2 details data processing, cleansing, and modeling plans to assess SIS ranging accuracy as per OS SDD v1.2, Section 3.3, Tables 9 and 10. This section will include SIS ranging accuracy results in upcoming Galileo quarterly reports.

Galileo Time Transfer Performance. Analysis of Galileo Time Transfer Performance will be incorporated in a future report. As is done with GPS time transfer analysis, a data product is needed from the U.S. Naval Observatory (USNO) comparing Galileo system time as computed by its users, with that of the Coordinated Universal Time (UTC) standard of time produced by the USNO and other labs. The evaluation of accuracy of Galileo's time dissemination service will follow the descriptions in OS SDD v1.2, Section 3.3.3, and the evaluation of availability of Galileo's time dissemination service will follow the descriptions in OS SDD v1.2 Sections 3.3.4, 3.42, and 3.45.

Availability of Galileo Positioning. In future reports this section will include data processing results assessing the availability of the Galileo positioning service at the worst user location and average user location as it relates to MPL commitments described in OS SDD v1.2, Section 3.4.4, Tables 16 and 17. The development of this section depends on the completed development of data processing, cleansing, and modeling detailed in Section 3.2. Using the dilution of precision modeled in Section 2 along with the signal-in-space ranging error, this section will present horizontal position error and vertical position error results modeled as described in OS SDD v1.2, Section C.4.5.3.

Galileo Position Accuracy. The Satellite Navigation Branch developed a Galileo dual frequency user position tool to measure position accuracy using Galileo. Galileo navigation data is collected from Novatel G-III and GT7800 receivers located at the FAA WJHTC and Elko, Nevada. The 95% vertical and horizontal position accuracy was calculated as a monthly statistic. The 95% horizontal position accuracy remained less than 1.6 m for October, November, and December. The 95% vertical position accuracy remained less than 2.2 m for October, November, and December.

Timely Publication of NAGUS. The timeliness of NAGUs is determined based on the MPLs discussed in section 3.6.1 of the Galileo OS-SDD using NAGUs published to the European GNSS Service Center website [3]. There were five NAGUs published this quarter; two NAGUs were categorized as Planned, and two NAGUs were categorized as Unplanned. One NAGU was regarding high accuracy service (HAS), which is out of the scope of this report. Of the four Galileo Open Service NAGUs, all four were published in a timely manner.

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1. INTRODUCTION

In 2016, the EU made available the Galileo GNSS, providing ranging, navigation, and timing services to properly equipped users. Galileo is currently in its initial operational capability (IOC) phase. Galileo is a GNSS similar to the U.S. GPS. Galileo and GPS are interoperable and transmit signals on the same frequencies.

Galileo provides five services: OS, Safety-of-Life Service, Commercial Service, High Availability Service, and Public Regulated Service [4]. The scope of this report is limited to the OS, specifically the E1 and E5a signals. The Galileo signals applicable to the OS are E1 (1575.42 MHz, the same frequency as GPS L1), E5a (1176.45 MHz, the same frequency as GPS L5), and E5b (1207.14 MHz). The E1 and E5a frequencies and modulation scheme correspond to GPS L1 and L5 to simplify the combined use of both constellations.

The FAA will evaluate Galileo performance while it is still in its IOC phase. Internationally, standards organizations are preparing specifications for aviation use of Galileo. To prepare for the future use of Galileo in aviation, performance monitoring of Galileo is necessary to assess the performance and characteristics of the system. Note that the European Union Agency for the Space Programme (EUSPA) also publishes Galileo performance reports on their website [5].

This report focuses exclusively on Galileo performance. The FAA publishes a separate report on GPS performance and ARAIM performance. ARAIM is a dual-frequency/multi-constellation scheme that uses GPS and Galileo in an aviation application.

This report uses several sources of data for the evaluation. A G-III receiver located at the FAA WJHTC in Atlantic City, New Jersey and a GT7800 located in Elko, Nevada collect the Galileo signals directly. Future reports will include data from other Galileo-capable receivers to expand the footprint of this report's assessment of Galileo. Other sources of data include Galileo broadcast navigation data from the IGS and precise Galileo ephemeris and clock data from the Center for Orbit Determination in Europe (CODE). This report later explains the use of these offline data sources.

The Galileo performance assessment evaluates parameters in the Galileo OS SDD, version 1.2. The EU published version 1.2 of the OS SDD in November 2021, updating some MPLs associated to these parameters. The parameters included in this report or future reports are:

- Signal-in-Space (SIS) Ranging Accuracy
- SIS Ranging Rate Accuracy
- Galileo Time Transfer Accuracy and Availability (Future Report)
- Per Slot Availability
- Dilution of Precision (DOP) Availability
- Positioning Service Availability
- Timely Publication of NAGU

- User Position Error (this parameter is not in the OS SDD)

The MPLs for each of the parameters evaluated are in the applicable section of this report.

Note that two Galileo constellation "auxiliary" satellites, Space Vehicle Identification (SVID) numbers 14 and 18, were set unhealthy on February 18, 2021. An explanation for this is provided in Galileo Service Notice #05. This report does not include those two satellites in the performance assessment.

2. AVAILABILITY OF GALILEO PDOP

The availability of Galileo PDOP is the percentage of time the PDOP remains less than or equal to a threshold for any point in the Galileo service coverage. DOP is the effect on user position errors induced by the satellite geometry used in the position measurement solution. The Galileo OS SDD defines the availability of Galileo PDOP to be the percentage of time the PDOP remains less than or equal to 6 with a minimum of 4 Galileo satellites visible above a 5-degree elevation transmitting healthy SIS (satellite health described in OS SDD Section 2.3.1). On a global basis, the availability of PDOP is computed as the average over all user locations within the service coverage (service coverage described in OS SDD Annex C.3 [2]), provided as a monthly statistic.

Table 2-1 specifies the MPL for the availability of PDOP according to the OS SDD.

Table 2-1. Availability of PDOP Parameter

MPL of the Availability of PDOP	Conditions and Constraints
≥ 90% average user location	• PDOP <= 6 • At least 4 satellites in view with a minimum elevation angle of 5 degrees • Calculated for 30-day period • Includes planned and unplanned outages

The Satellite Navigation Branch at the FAA WJHTC developed a Galileo coverage area tool to calculate DOPs (horizontal dilutions of precision (HDOPs), vertical dilutions of precision (VDOPs), and PDOPs) using the Galileo constellation. Galileo ephemerides were obtained from broadcast Galileo data provided by IGS [9]. Galileo ephemerides were incorporated into the DOP calculation using the status of both E1b and E5a being healthy at the same time. Using satellite health status from worldwide Galileo ephemeris data accounts for satellite maintenance and outages, including NAGUs. Galileo auxiliary satellites E10, E14, and E18 were not included in the calculations and data provided in this section. DOPs were calculated at every 2-degree grid between longitudes 180W to 180E and latitudes 74S to 74N at 1-minute time intervals. This resulted in 1440 samples for each of the 13,500 grid points over a 24-hour period. See APPENDIX A: GLOBAL MAXIMUM PDOP TREND for a plot of the maximum PDOP computed at each timestep on this grid. Table 2-2 provides the results of the monthly Availability of PDOP (computed as an average of the 2-degree coverage area described above).

Table 2-2. Availability of PDOP

Month	Availability of PDOP (Galileo OS SDD MPL: ≥ 90%)
October 2023	99.6425%
November 2023	99.556%
December 2023	99.6427%

Figure 2-1 through Figure 2-3 show a monthly contour plot of the availability of PDOP at each 2x2 degree grid point calculated for the Galileo coverage area. Inside each contour area, the availability of PDOP percentage is greater than or equal to the contour value shown in the legend for that color line. That area's value is also less than the next higher contour value unless another contour line lies within the current area. Please note the contour color values for Figure 2-1 through Figure 2-3 may vary for each plot.

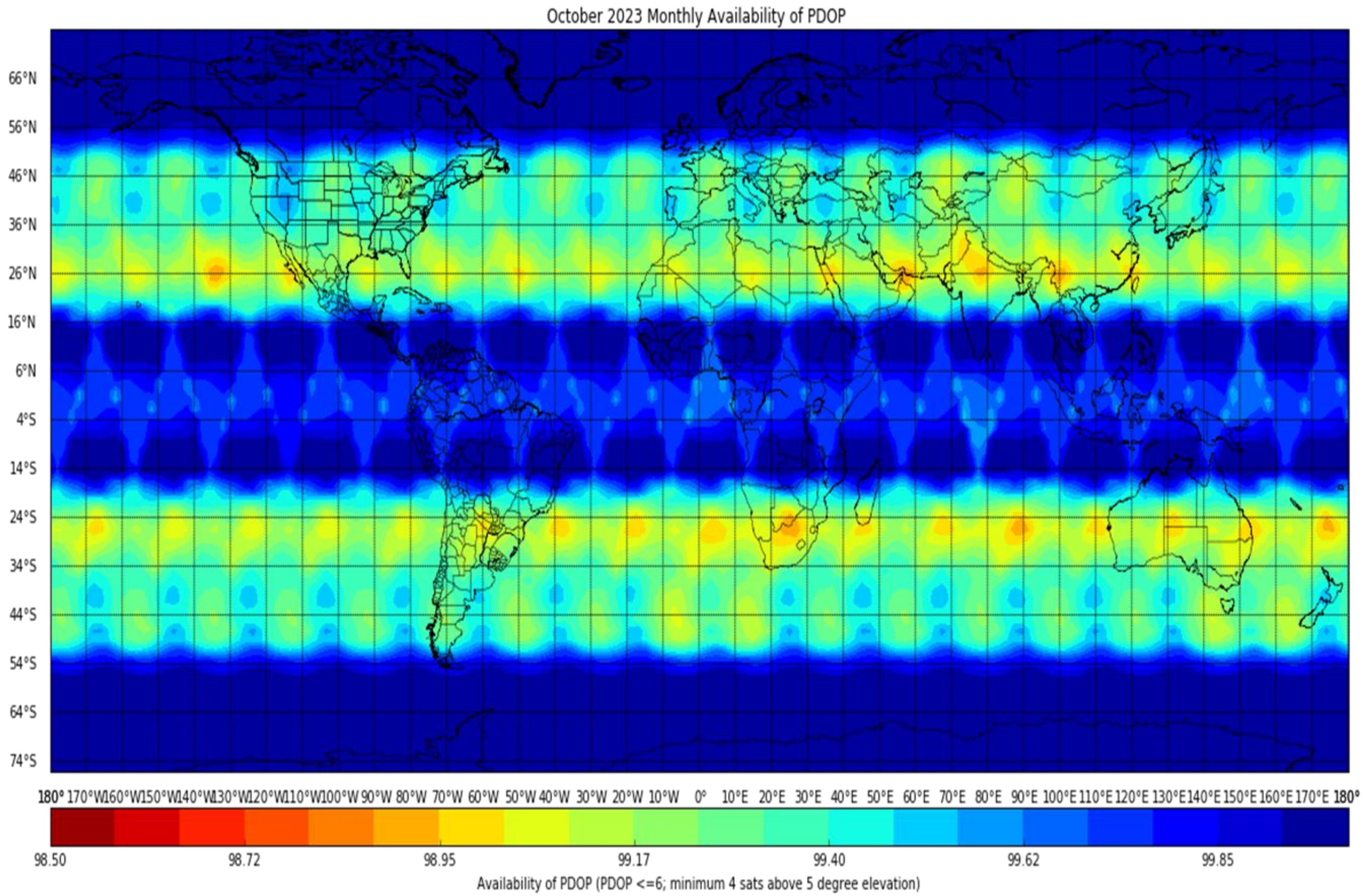


Figure 2-1. Availability of Galileo PDOP October 2023 (PDOP Availability Contour Color Bar: 98.5%–100%)

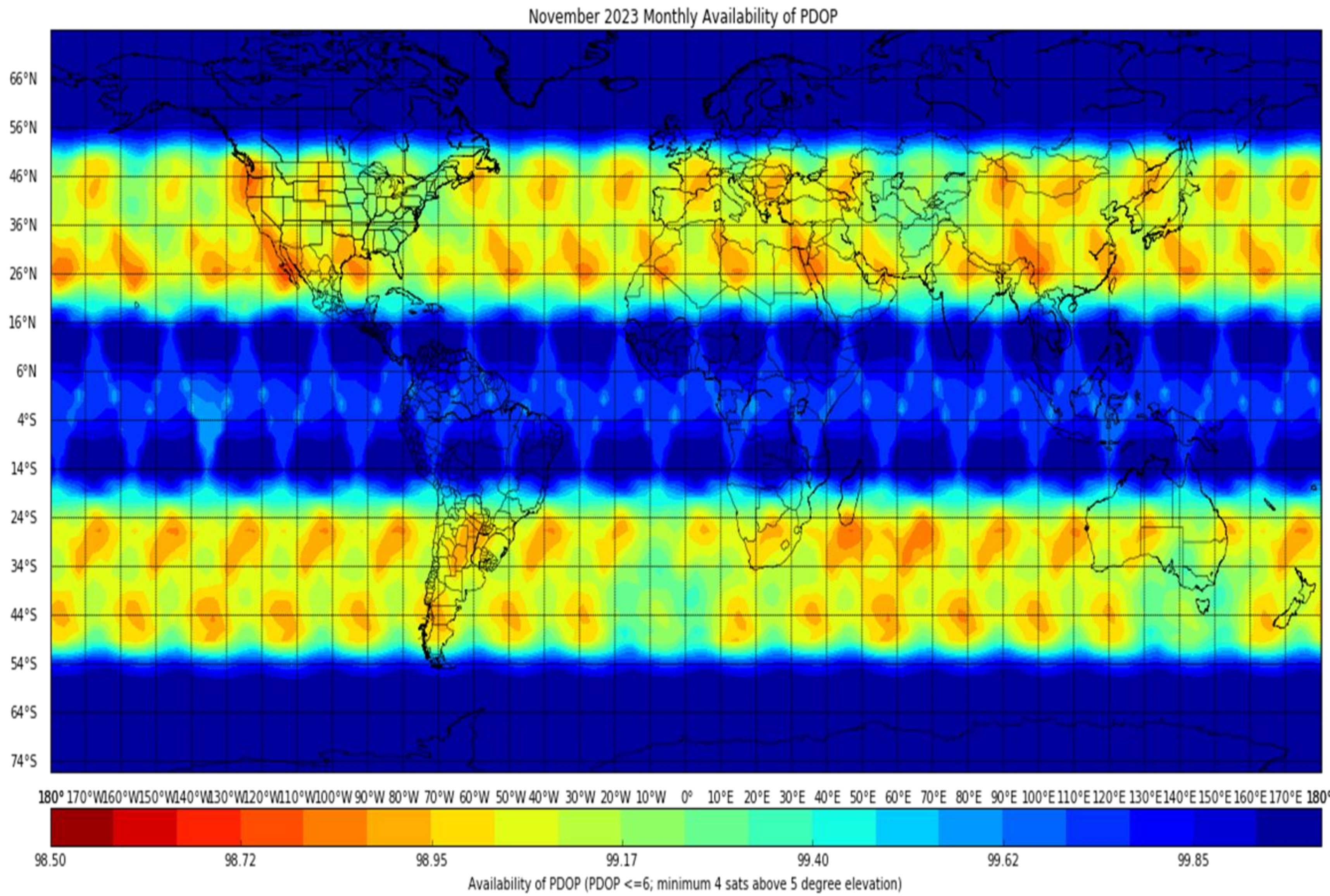


Figure 2-2. Availability of Galileo PDOP November 2023 (PDOP Availability Contour Color Bar: 98.5%–100%)

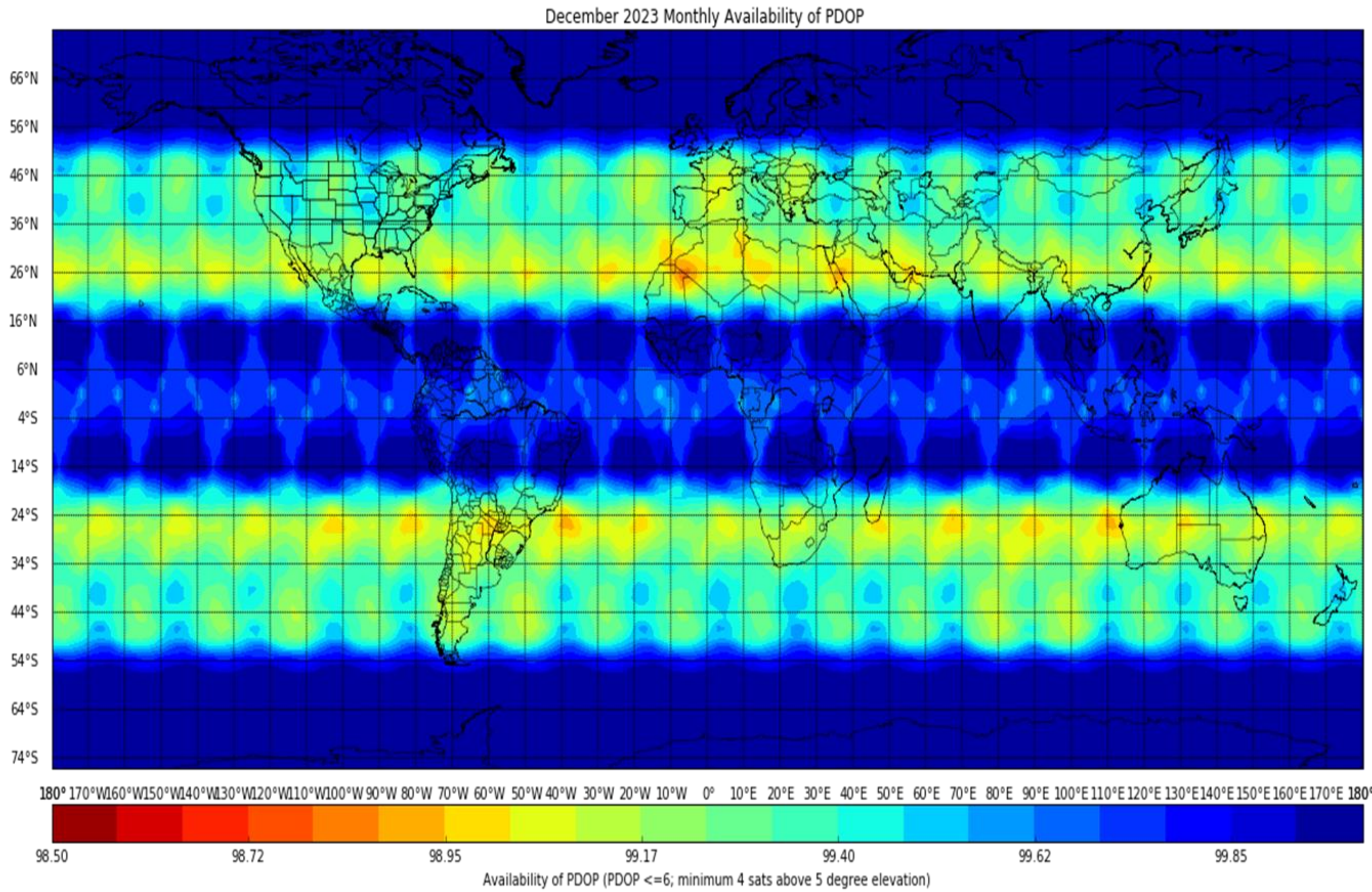
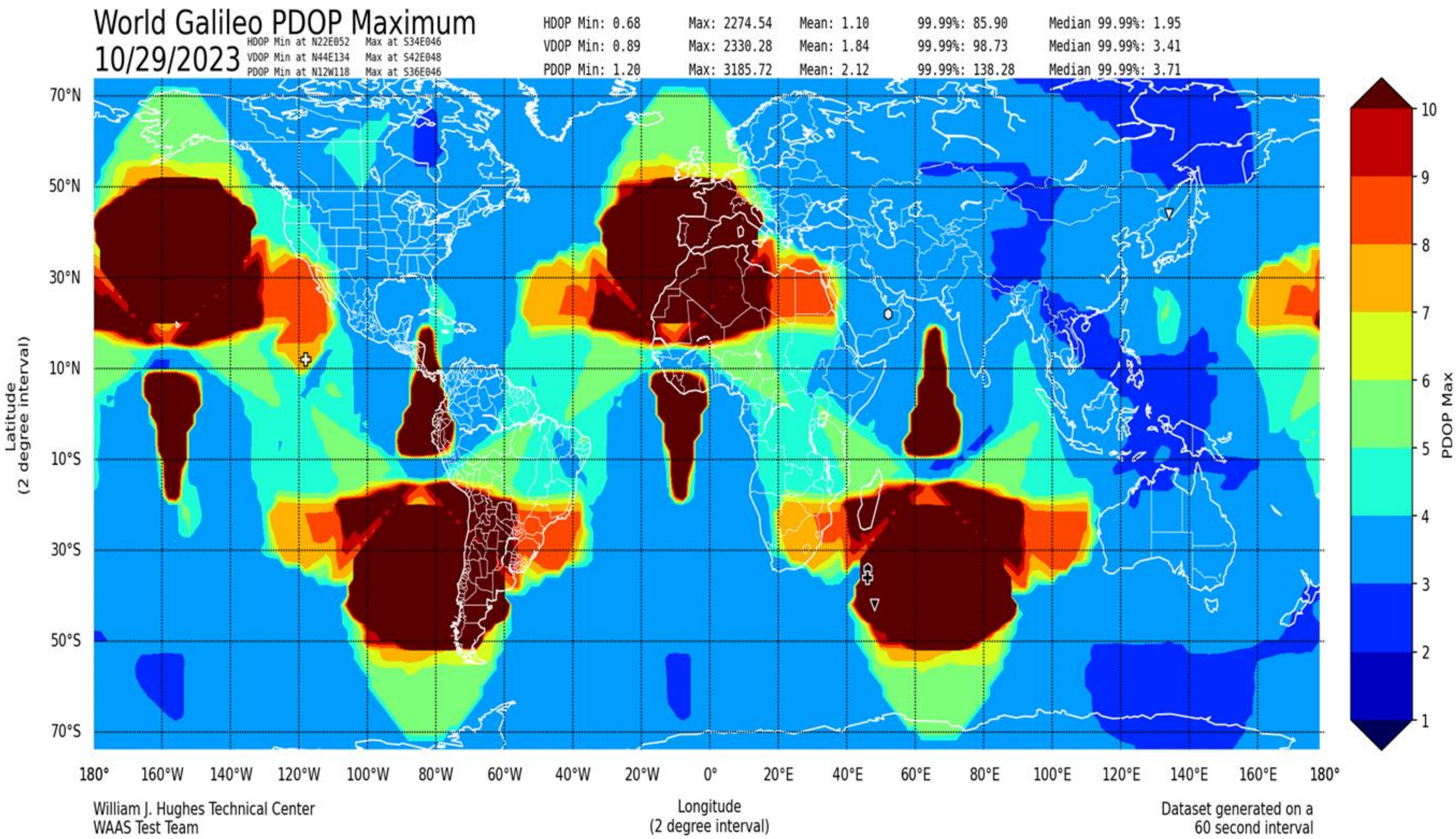


Figure 2-3. Availability of Galileo PDOP December 2023 (PDOP Availability Contour Color Bar: 98.5%–100%)

Figure 2-4 shows a contour plot of the maximum PDOP values at each 2-degree grid point for a 24-hour period. Figure 2-4 also shows PDOP performance using a day with no NAGUs or events affecting PDOP. Galileo constellation ground tracks have a 10-day repeatability cycle; therefore, consecutive 24-hour PDOP plots will not be repeatable day to day. APPENDIX B: GALILEO DAILY MAXIMUM PDOP 10-DAY GEOMETRY CYCLE COMPARISON provides 10-day spatial PDOP plots to compare similar geometries.



+ ▼ ⬣ = location of maximum PDOP, VDOP, and HDOP, respectively

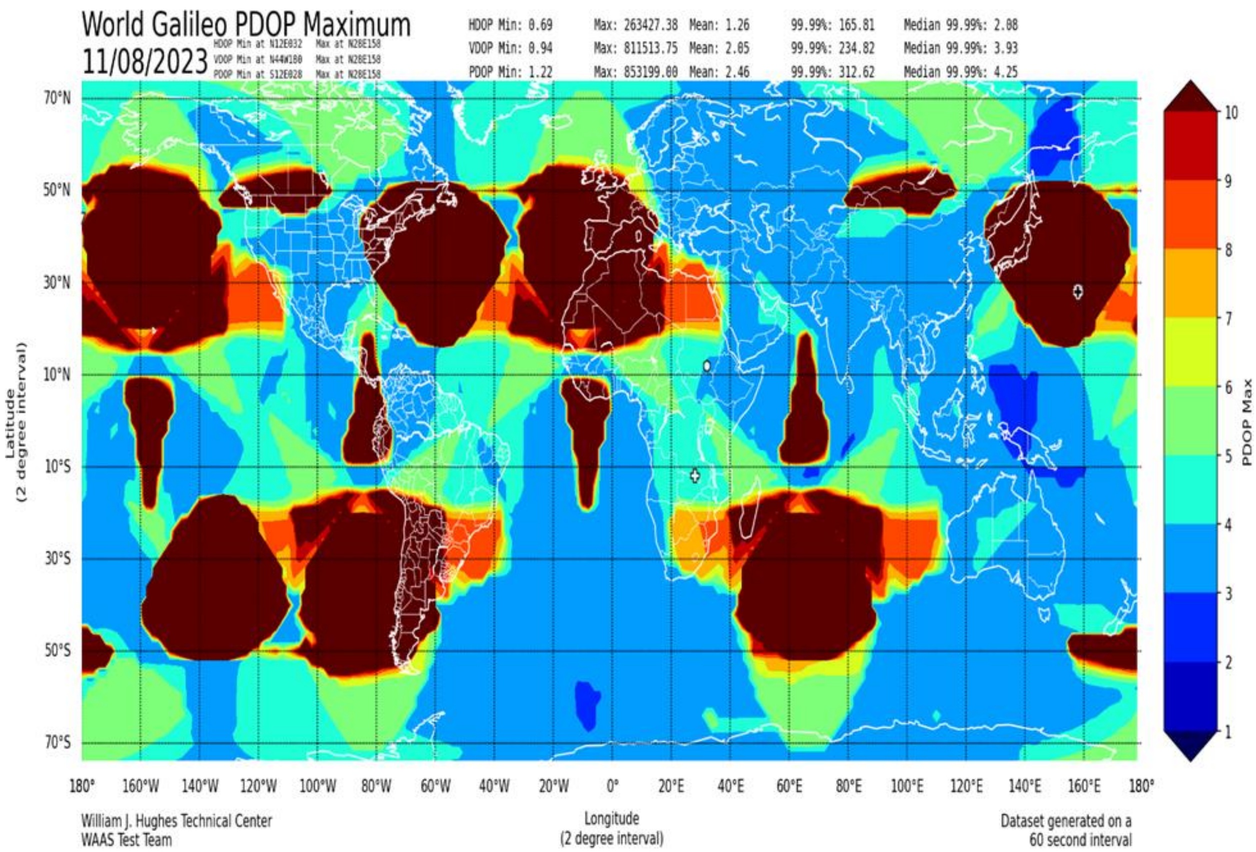
✙ ▽ ⬡ = location of minimum PDOP, VDOP, and HDOP, respectively

Figure 2-4. World Galileo Maximum PDOP (October 29, 2023)

Events that affect Galileo PDOP are often due to satellite planned or unplanned outages. NAGUs provide information of forecasted satellite outages and summarize times satellites were unusable after the event. This quarter had one NAGU event that affected Galileo PDOP.

SVID 5 was unusable from 06:15 GMT on November 7, 2023 until 18:05 GMT on November 16, 2023 (NAGUs 2023054 and 2023055). Figure 2-5 shows the maximum PDOP plot for November 8, 2023 (NAGU 2023055), and Figure 2-4 shows the maximum PDOP plot on October 29, 2023 with no events.

Section 3.1 details the satellite health during this time period, and Section 6 provides NAGU information.



+ ▼ ⬣ = location of maximum PDOP, VDOP, and HDOP, respectively
✜ ▽ ⬡ = location of minimum PDOP, VDOP, and HDOP, respectively

Figure 2-5. World Galileo Maximum PDOP (November 8, 2023) With SVID 5 Set Unhealthy

+ ▼ ⬣ = location of maximum PDOP, VDOP, and HDOP, respectively
✜ ▽ ⬡ = location of minimum PDOP, VDOP, and HDOP, respectively

3. SIGNAL HEALTH AND ACCURACY (F/NAV)

3.1 Healthy Signal Summary

The Galileo OS SDD v1.2, Section 2.3.1.4 discusses the mapping of SIS status flags with the signal status. Figure 3-1 shows the percentage of time that the E5a signal received at WJHTC with a WAAS G-III receiver demodulated F/NAV data that would be classified as healthy following the decision tree described in Figure 4 of the OS SDD v1.2. For this section, currently implemented data sources limit evaluation to the sky visible in Atlantic City. Future reports will seek to evaluate the MPL commitments in OS SDD, Section 3.4.1, which require worldwide signal tracking. During Q4 2023, 1,342,892 F/NAV subframes across 23 SVIDs were evaluated. Auxiliary satellites E14 and E18 are not included in the evaluation.

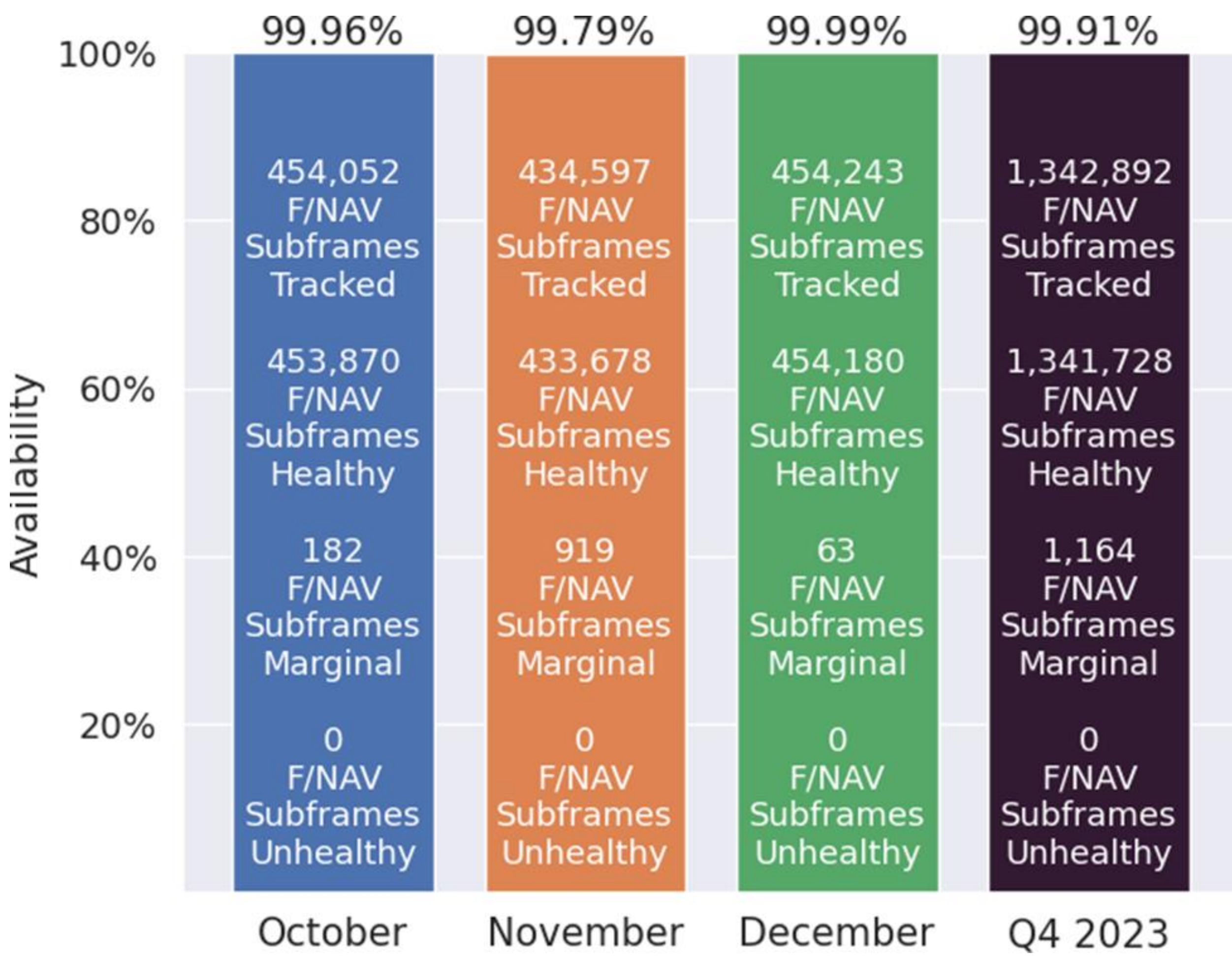


Figure 3-1. Percentage of Time Healthy F/NAV Subframes Tracked From WJHTC

Table 3-1 provides a count of each individual F/NAV subframe received with the NovAtel G-III receiver at WJHTC, grouping the SVID counts by $E5A_{DVS}$, $E5A_{HS}$, and SISA. The same data is presented in Table 3-2 where the grouping instead begins with the SVID followed by the $E5A_{DVS}$, $E5A_{HS}$, and SISA index.

Table 3-1. Q4 2023 F/NAV E5a Subframe Counts by $E5A_{DVS}$, $E5A_{HS}$, SISA and SVID

E5A_DVS	E5A_HS	SISA	SVID	# of Subframes
0	0	107	2	58811
			3	58568
			4	58257
			5	52628
			7	58296
			8	58112
			9	58509
			10	59028
			11	58437
			12	58528
			13	58813
			15	58834
			19	57173
			21	58092
			24	59052
			25	58703
			26	58772
			27	58063
			30	58688
			31	59127
			33	58798
			34	59202
			36	59237
		255	5	901
1	0	107	3	31
			4	63
			5	22
			7	23
			25	40
			27	3
			33	81

Table 3-2. Q4 2023 F/NAV E5a Subframe Counts by SVID, $E5A_{DVS}$, $E5A_{HS}$, and SISA

SVID	E5A_DVS	E5A_HS	SISA	# of Subframes
2	0	0	107	58811
3	0	0	107	58568
	1	0	107	31
4	0	0	107	58257
	1	0	107	63
5	0	0	107	52628
			255	901
	1	0	107	22
7	0	0	107	58296
	1	0	107	23
8	0	0	107	58112
9	0	0	107	58509
10	0	0	107	59028
11	0	0	107	58437
12	0	0	107	58528
13	0	0	107	58813
15	0	0	107	58834
19	0	0	107	57173
21	0	0	107	58092
24	0	0	107	59052
25	0	0	107	58703
	1	0	107	40
26	0	0	107	58772
27	0	0	107	58063
	1	0	107	3
30	0	0	107	58688
31	0	0	107	59127
33	0	0	107	58798
	1	0	107	81
34	0	0	107	59202
36	0	0	107	59237

3.1.1 Monthly F/NAV Signal Health Tracked at WJHTC

Figure 3-2, Figure 3-3, and Figure 3-4 show the F/NAV health status of the Galileo SVIDs tracked with a NovAtel G-III receiver at WJHTC in Atlantic City for each month in the quarter. Healthy F/NAV subframes are marked with smaller glyphs colored green, marginal subframes are colored magenta, and unhealthy subframes are colored red.

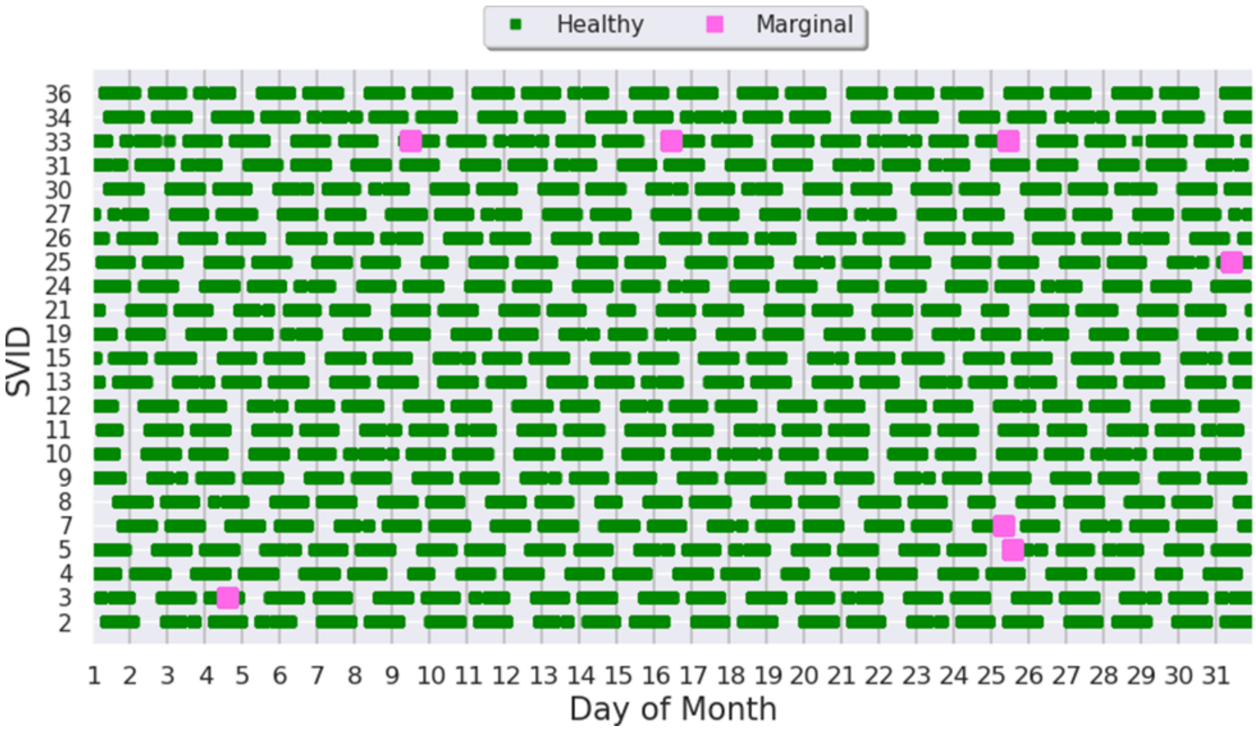


Figure 3-2. F/NAV Signal Health by SVID (Tracked at WJHTC October 2023)

Figure 3-3. F/NAV Signal Health by SVID (Tracked at WJHTC November 2023)

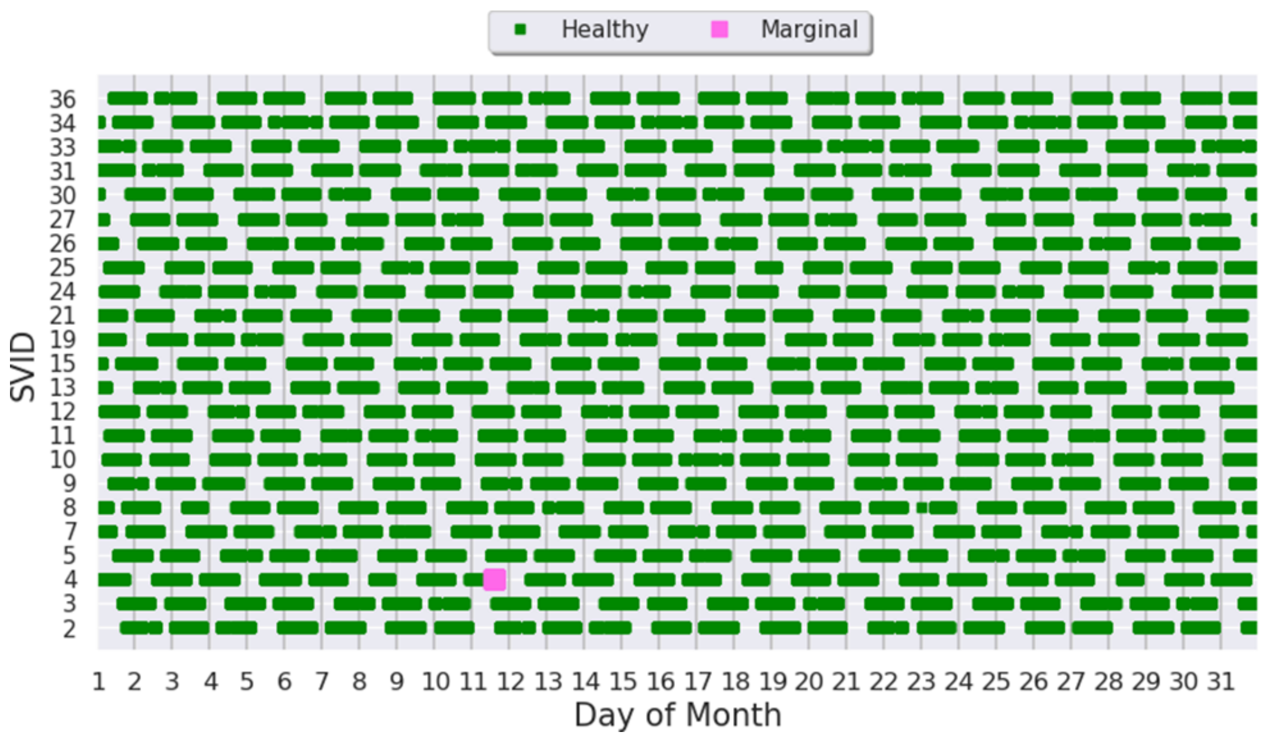


Figure 3-4. F/NAV Signal Health by SVID (Tracked at WJHTC December 2023)

3.1.2 F/NAV Signal Health Events Tracked at WJHTC

This section examines in closer detail the F/NAV Page 1 SISA index, $E5A_{DVS}$, $E5A_{HS}$, and F/NAV Pages 1–4 IODnav during 12 events in Q4 2023 when F/NAV signals were detected with a NovAtel G-III receiver at WJHTC in Atlantic City to be in a state other than healthy.

3.1.2.1 SVID 3 October 4, 2023

On October 4 at 14:05:00 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to E5a DVS flag indicating working without guarantee in the F/NAV subframe with IOD_{nav} 3. The signal was last seen healthy on October 4 at 14:04:10 with F/NAV subframe IOD_{nav} 3 and first seen to return to a healthy state on October 4 at 14:30:50 UTC with F/NAV subframe IOD_{nav} 5 (see Figure 3-5).

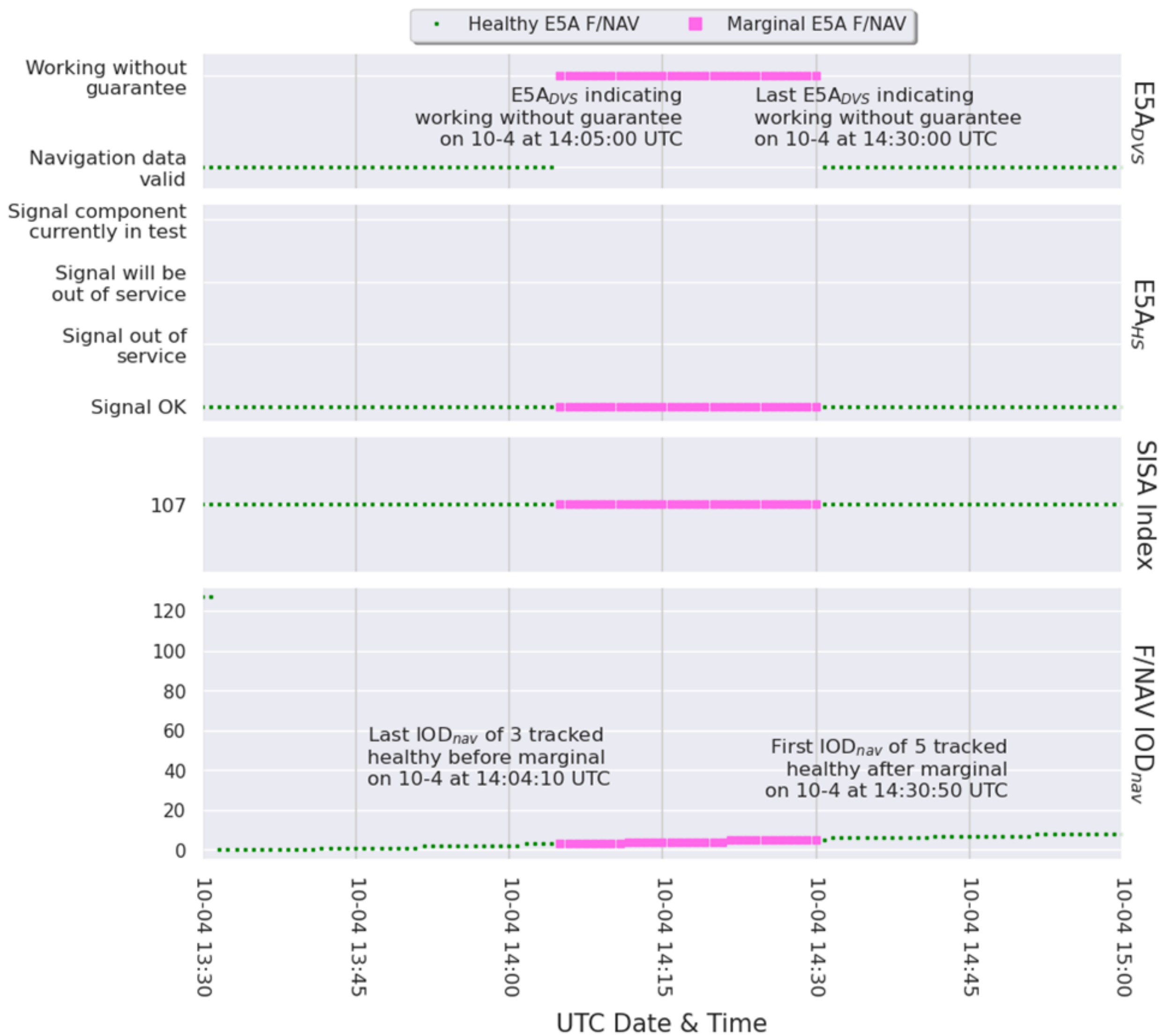


Figure 3-5. Marginal F/NAV Signal (SVID 3 Tracked at WJHTC October 4)

3.1.2.2 SVID 33 October 9, 2023

On October 9 at 10:52:30 UTC the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS indicating working without guarantee in the F/NAV subframe with IOD_{nav} 80. The signal was last seen healthy on October 9 at 10:51:40 UTC with F/NAV subframe IOD_{nav} 80 and first seen to return to a healthy state on October 9 at 11:12:30 UTC with F/NAV subframe IOD_{nav} 80 (see Figure 3-6).

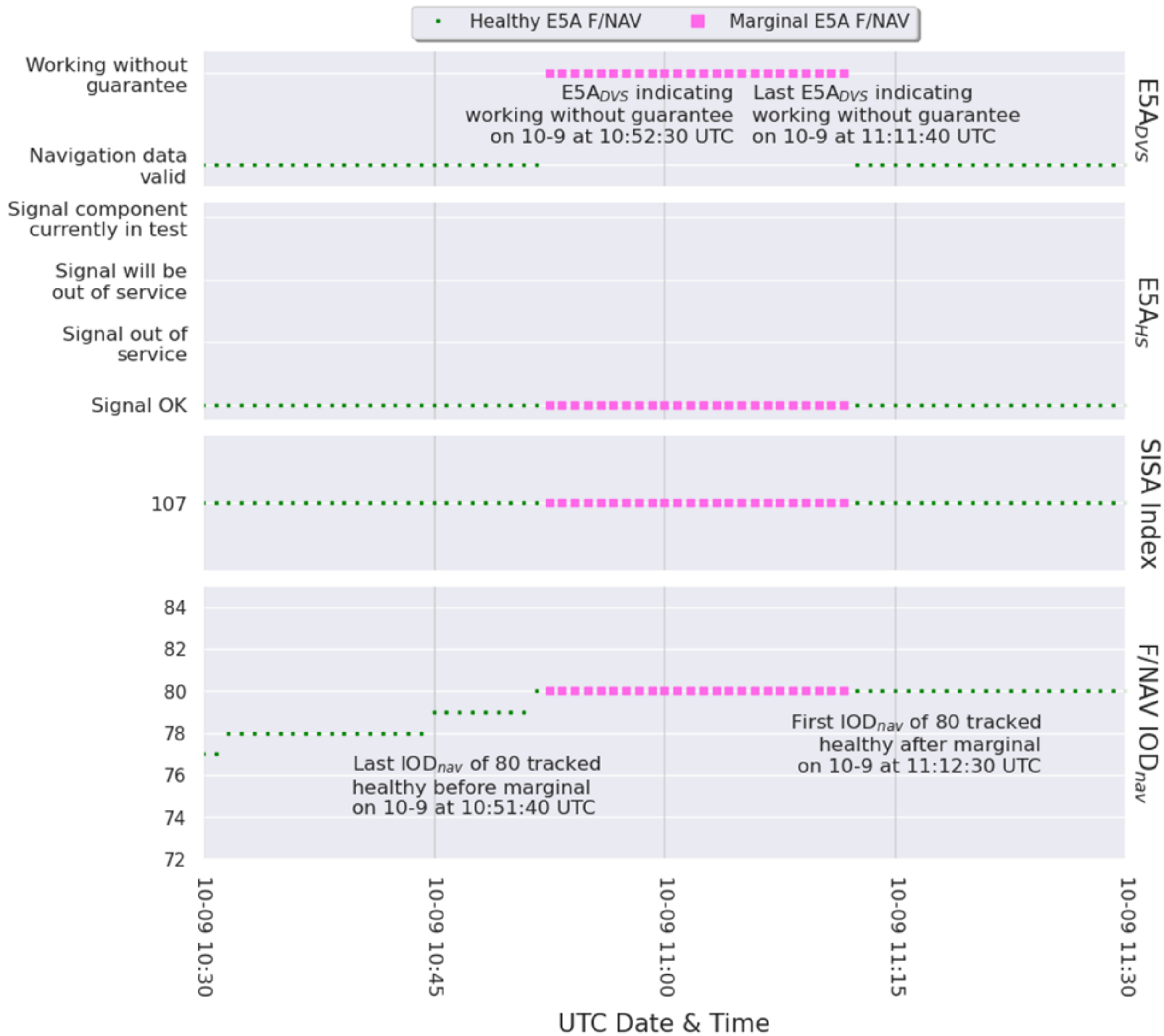


Figure 3-6. Marginal F/NAV Signal (SVID 33 Tracked at WJHTC October 9)

3.1.2.3 SVID 33 October 16, 2023

On October 16 at 10:10:50 UTC the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS indicating working without guarantee in the F/NAV subframe with IOD_{nav} 75. The signal was last seen healthy on October 16 at 10:10:00 UTC with F/NAV subframe IOD_{nav} 75 and first seen to return to a healthy state on October 16 at 10:39:10 UTC with F/NAV subframe IOD_{nav} 78 (see Figure 3-7).

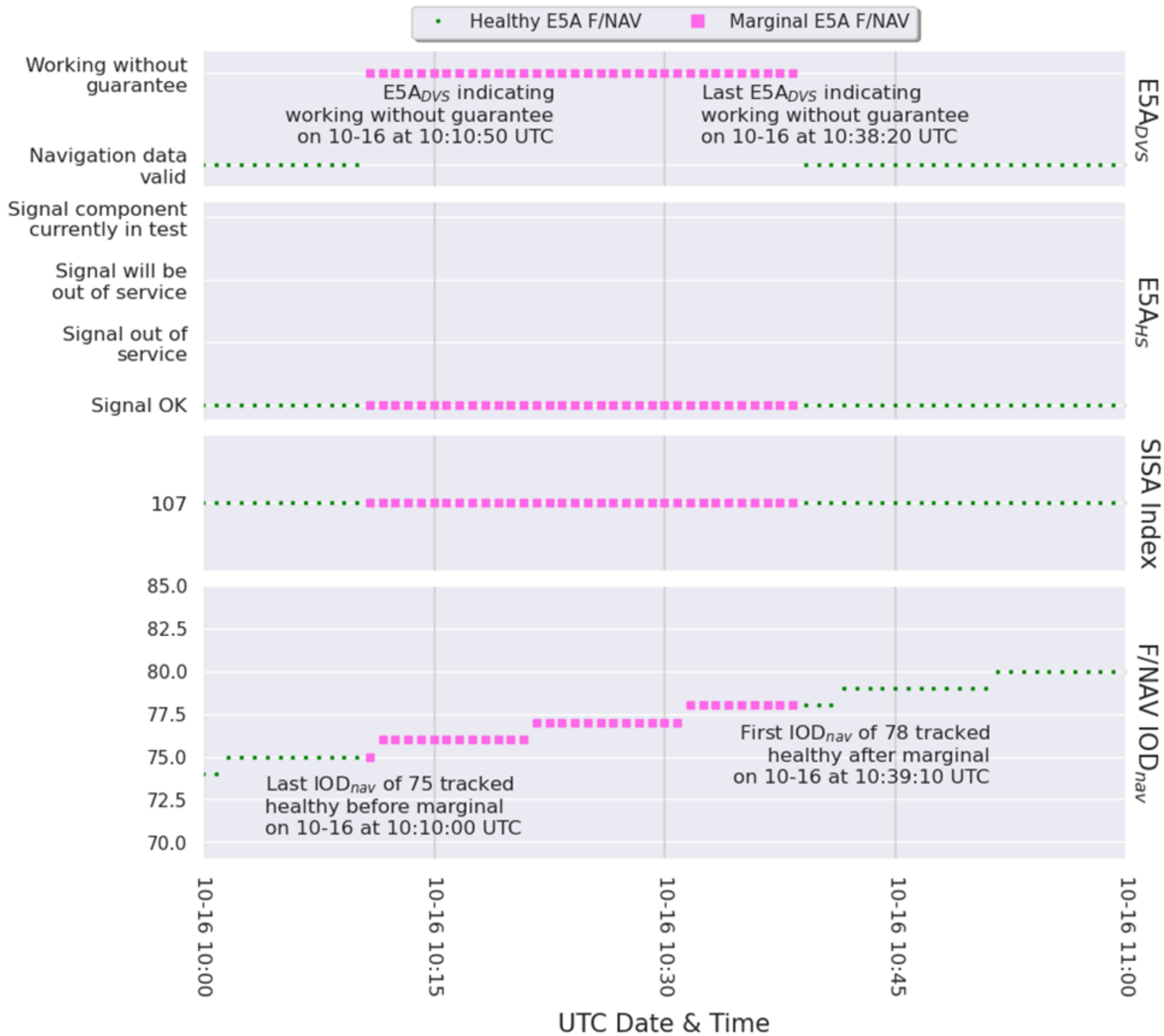


Figure 3-7. Marginal F/NAV Signal (SVID 33 Tracked at WJHTC October 16)

3.1.2.4 SVID 7 October 25, 2023

On October 25 at 07:18:20 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS signal indicating working without guarantee in the F/NAV subframe with IOD_{nav} 90. The signal was last seen healthy on October 25 at 07:17:30 with F/NAV subframe IOD_{nav} 90 and first seen to return to a healthy state on October 25 at 07:37:30 UTC with F/NAV subframe IOD_{nav} 92 (see Figure 3-8).

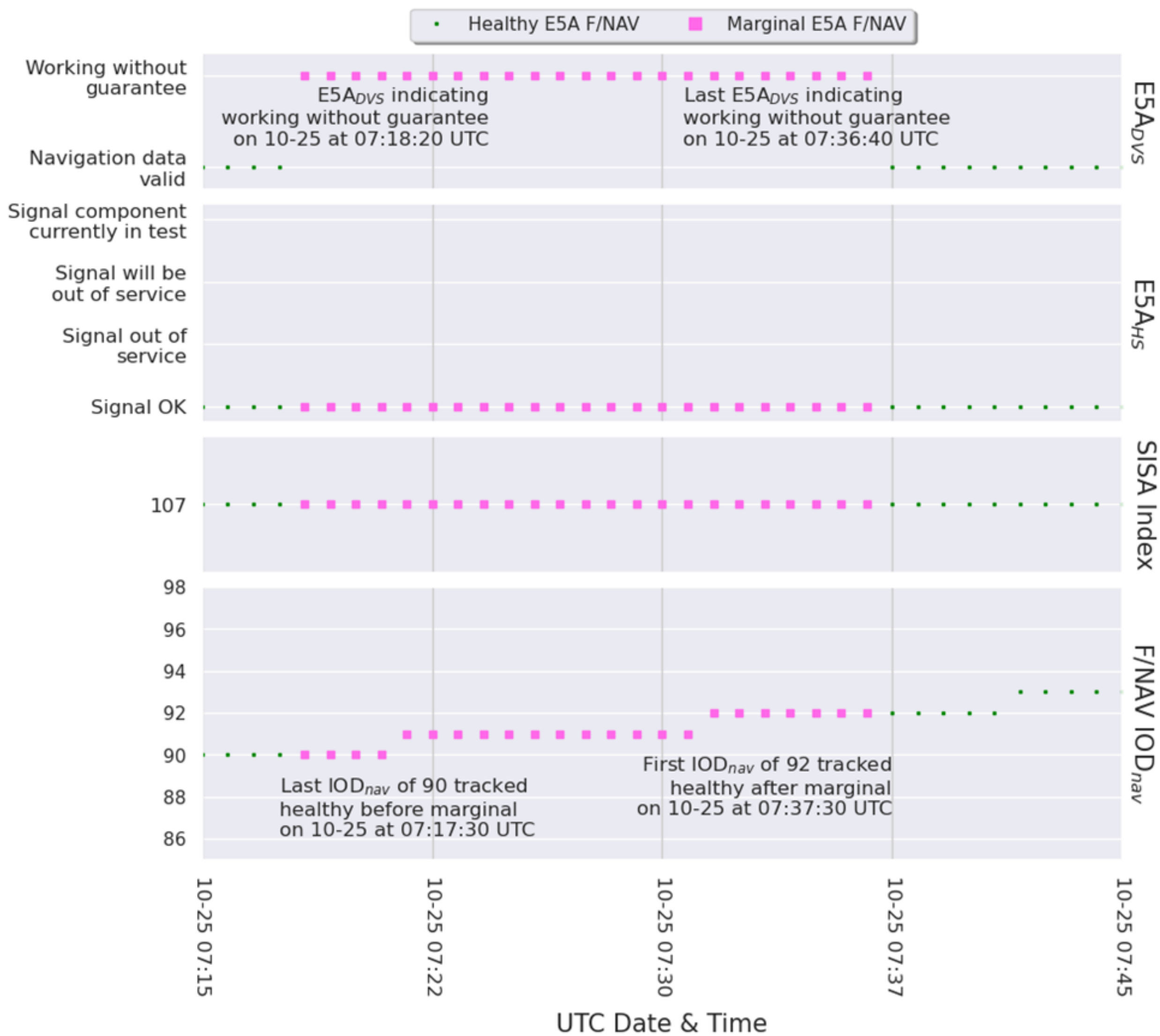


Figure 3-8. Marginal F/NAV Signal (SVID 7 Tracked at WJHTC October 25)

3.1.2.5 SVID 33 October 25, 2023

On October 25 at 10:13:20 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS signal indicating working without guarantee in the F/NAV subframe with IOD_{nav} 108. The signal was last seen healthy on October 25 at 10:12:30 with F/NAV subframe IOD_{nav} 108 and first seen to return to a healthy state on October 25 at 10:32:30 with F/NAV subframe IOD_{nav} 110 (see Figure 3-9).

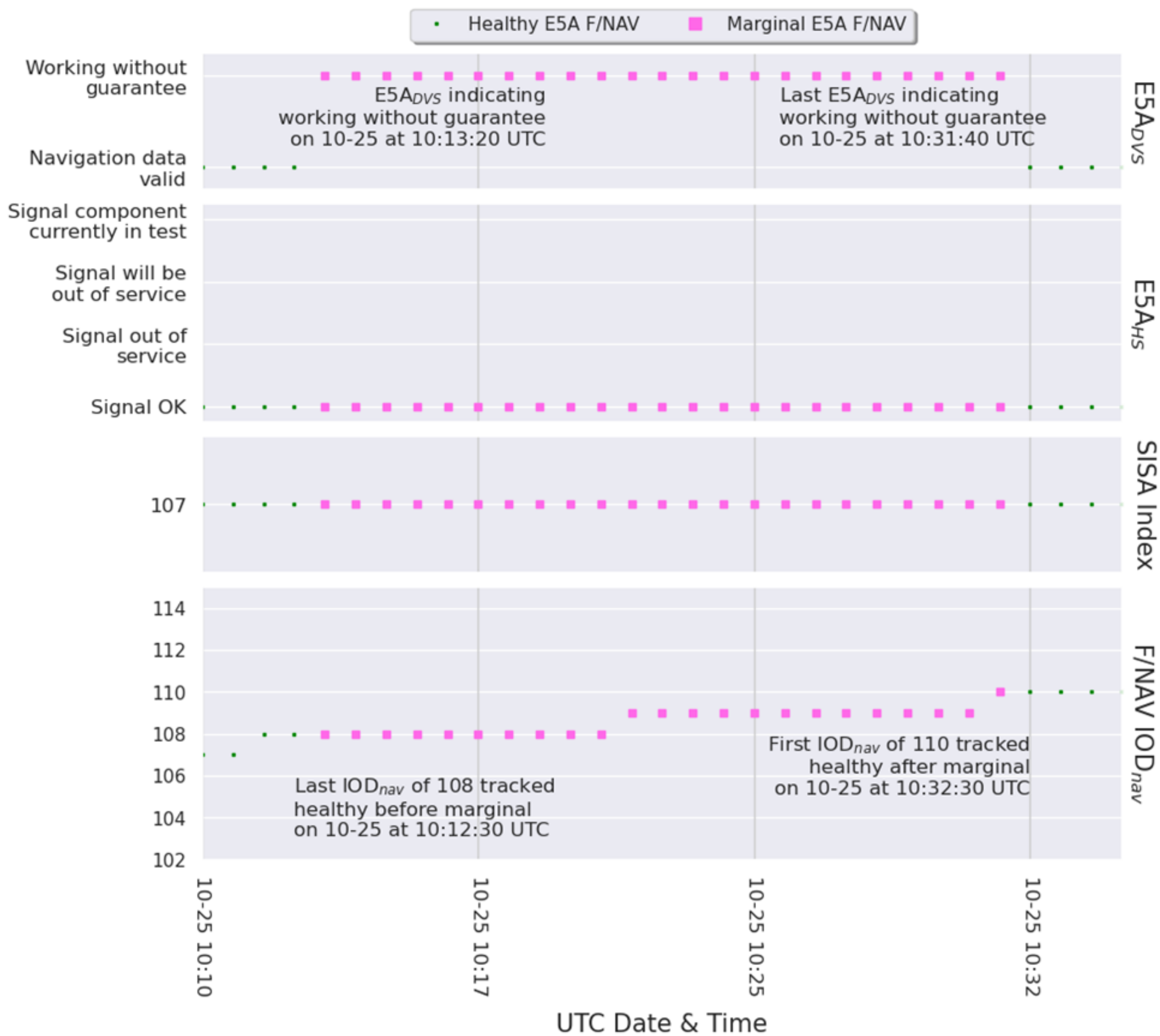


Figure 3-9. Marginal F/NAV Signal (SVID 33 Tracked at WJHTC October 25)

3.1.2.6 SVID 5 October 25, 2023

On October 25 at 13:18:20 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS signal indicating working without guarantee in the F/NAV subframe with IOD_{nav} 126. The signal was last seen healthy on October 25 at 13:17:30 with F/NAV subframe IOD_{nav} 126 and first seen to return to a healthy state on October 25 at 13:36:40 with F/NAV subframe IOD_{nav} 0 (see Figure 3-10).

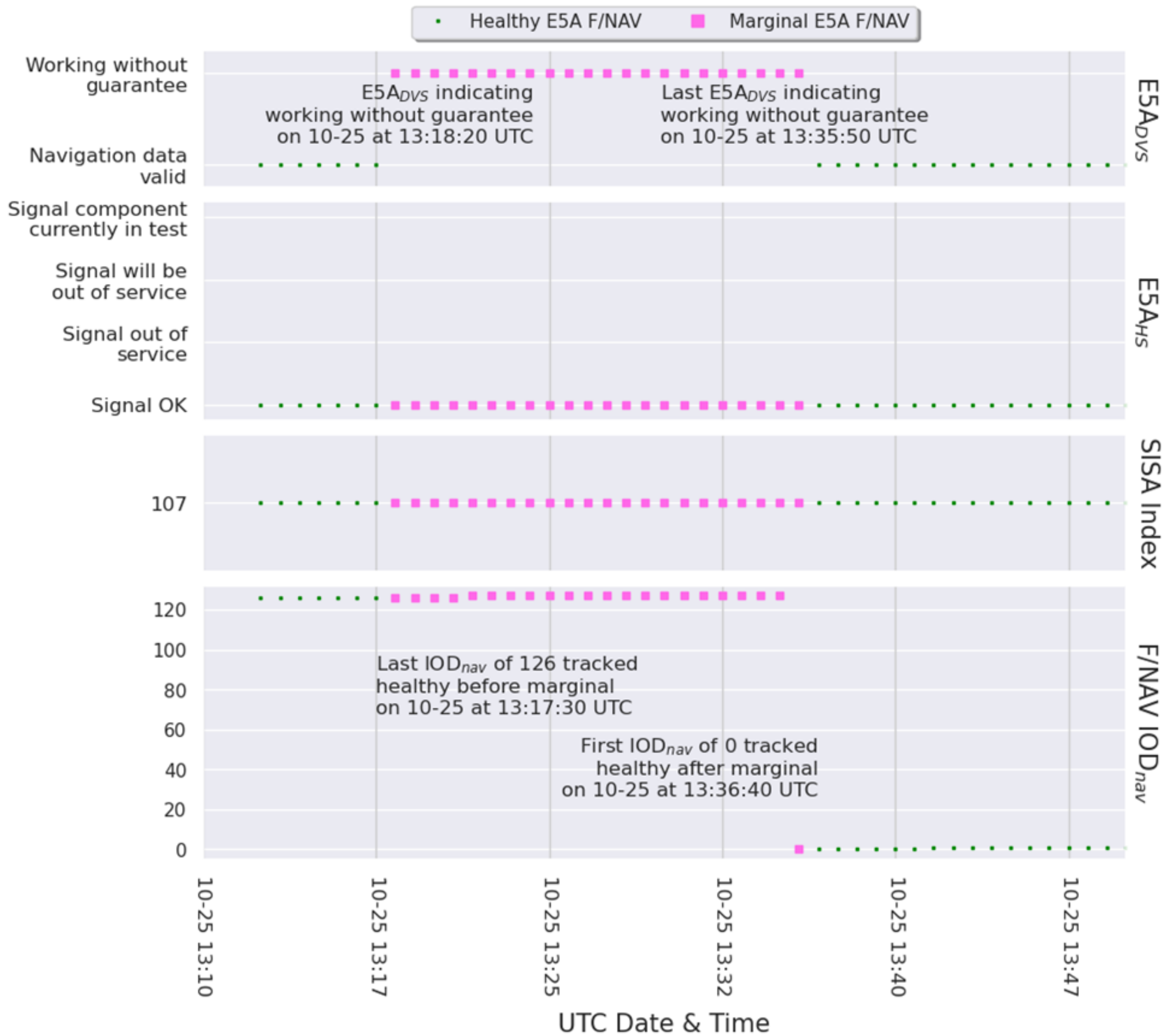


Figure 3-10. Marginal F/NAV Signal (SVID 5 Tracked at WJHTC October 25)

3.1.2.7 SVID 25 October 31, 2023

On October 31 at 09:15:00 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS signal indicating working without guarantee in the F/NAV subframe with IOD_{nav} 86. The signal was last seen healthy on October 31 at 09:14:10 with F/NAV subframe IOD_{nav} 86 and first seen to return to a healthy state on October 31 at 09:35:50 with F/NAV subframe IOD_{nav} 88 (see Figure 3-11).

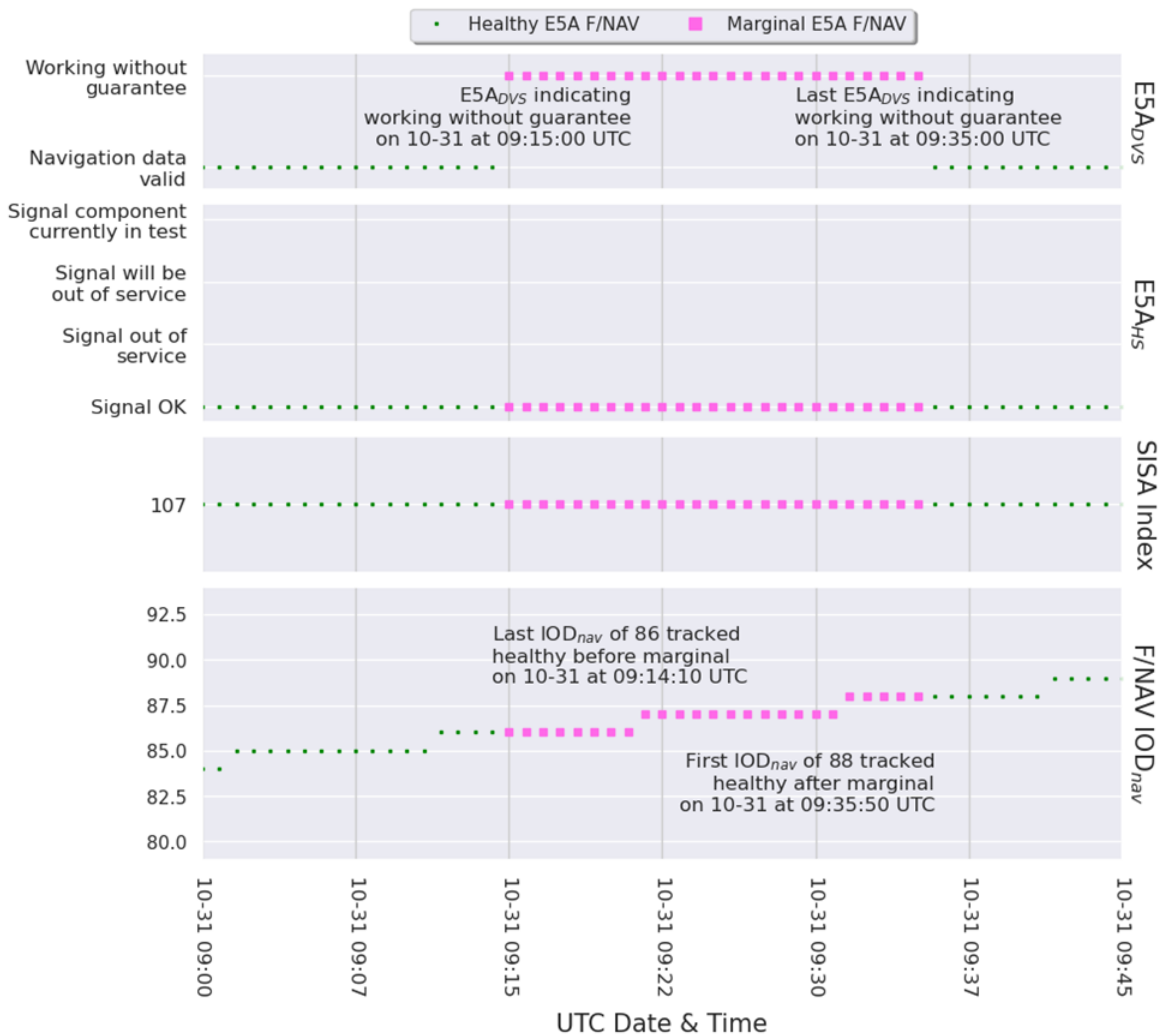


Figure 3-11. Marginal F/NAV Signal (SVID 25 Tracked at WJHTC October 31)

3.1.2.8 SVID 25 November 6, 2023

On November 6 at 13:25:00 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS signal indicating working without guarantee in the F/NAV subframe with IOD_{nav} 90. The signal was last seen healthy on November 6 at 07:22:30 with F/NAV subframe IOD_{nav} 59 and first seen to return to a healthy state on November 6 at 13:28:20 with F/NAV subframe IOD_{nav} 95 (see Figure 3-11).

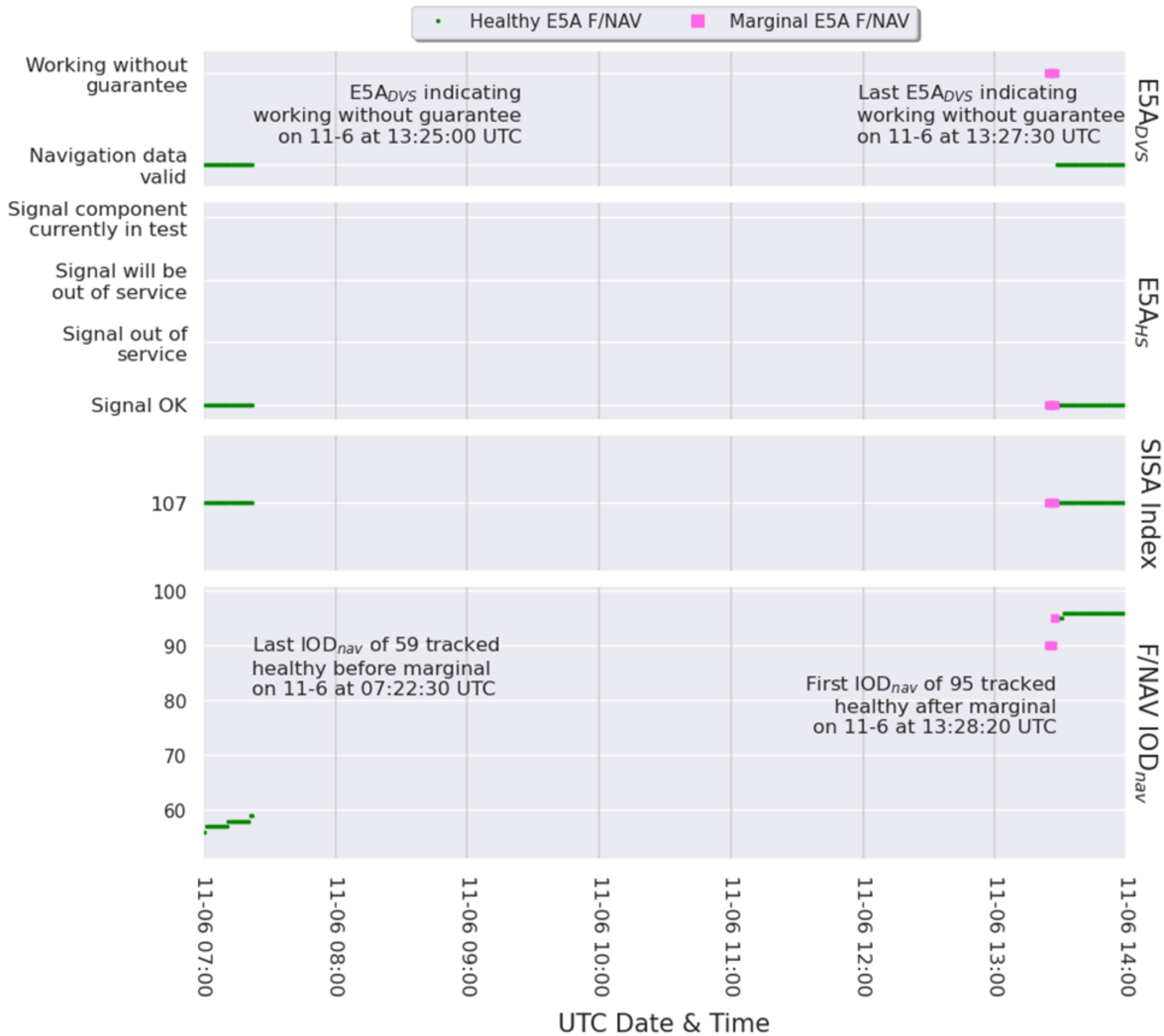


Figure 3-12. Marginal F/NAV Signal (SVID 25 Tracked at WJHTC November 6)

3.1.2.9 SVID 5 November 15–17, 2023

On November 15 at 20:01:40 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the SISA index indicating NAPA in the F/NAV subframe with IODnav 39. The signal was last seen healthy on November 7 at 03:20:50 with F/NAV subframe IODnav 47 and first seen to return to a healthy state on November 17 at 00:00:00 with F/NAV subframe IODnav 84 (see Figure 3-13).

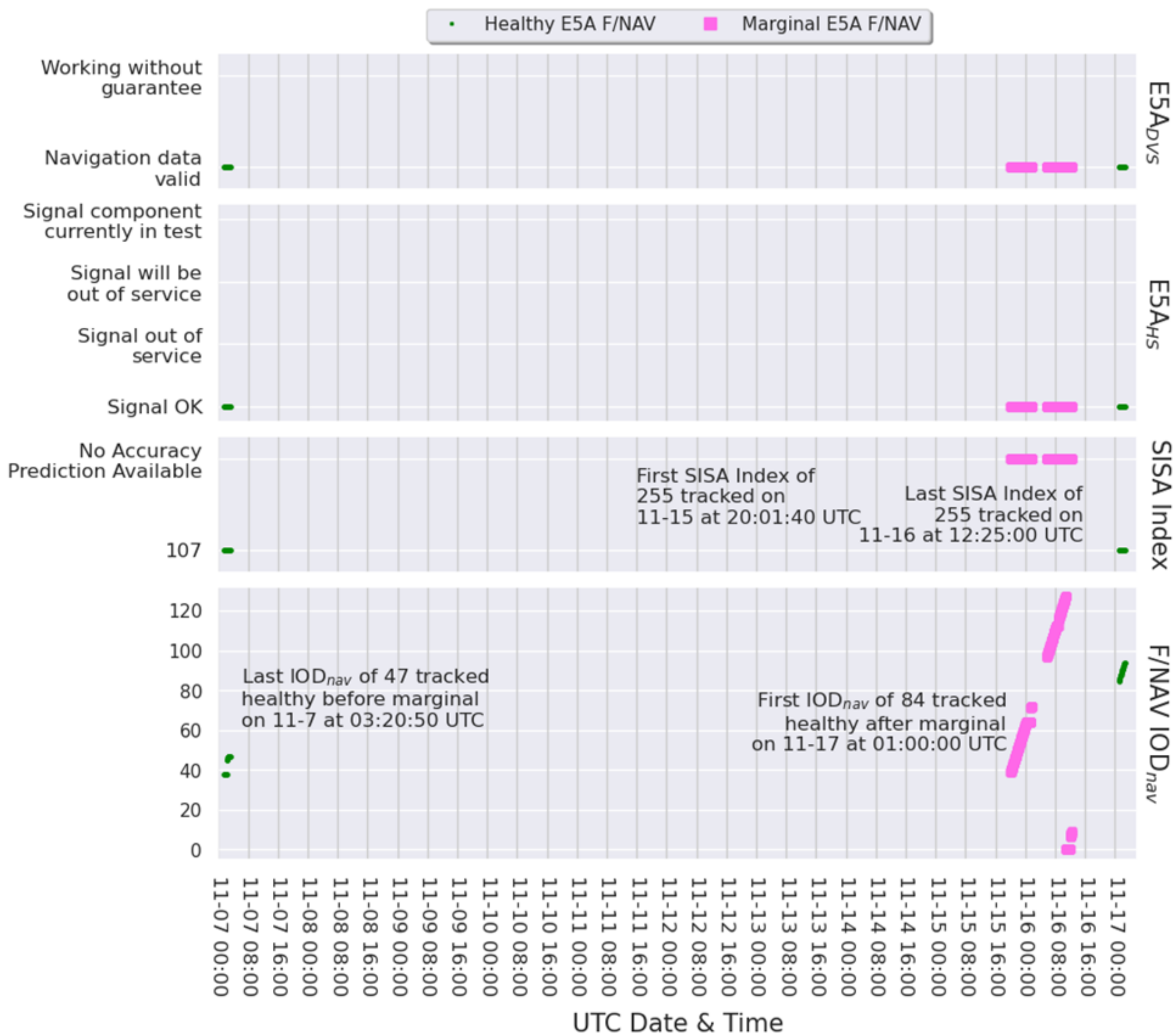


Figure 3-13. Marginal F/NAV Signal (SVID 5 Tracked at WJHTC November 15–17)

3.1.2.10 SVID 25 November 13, 2023

On November 13 at 13:11:40 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS signal indicating working without guarantee in the F/NAV subframe with IOD_{nav} 94. The signal was last seen healthy on November 13 at 08:24:10 with F/NAV subframe IOD_{nav} 65 and first seen to return to a healthy state on November 13 at 13:23:20 with F/NAV subframe IOD_{nav} 95 (see Figure 3-14).

Figure 3-14. Marginal F/NAV Signal (SVID 25 Tracked at WJHTC November 13)

3.1.2.11 SVID 27 November 20, 2023

On November 20 at 10:26:40 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS signal indicating working without guarantee in the F/NAV subframe with IOD_{nav} 73. The signal was last seen healthy on November 20 at 10:25:50 with F/NAV subframe IOD_{nav} 73 and first seen to return to a healthy state on November 20 at 18:15:00 with F/NAV subframe IOD_{nav} 122 (see Figure 3-15).

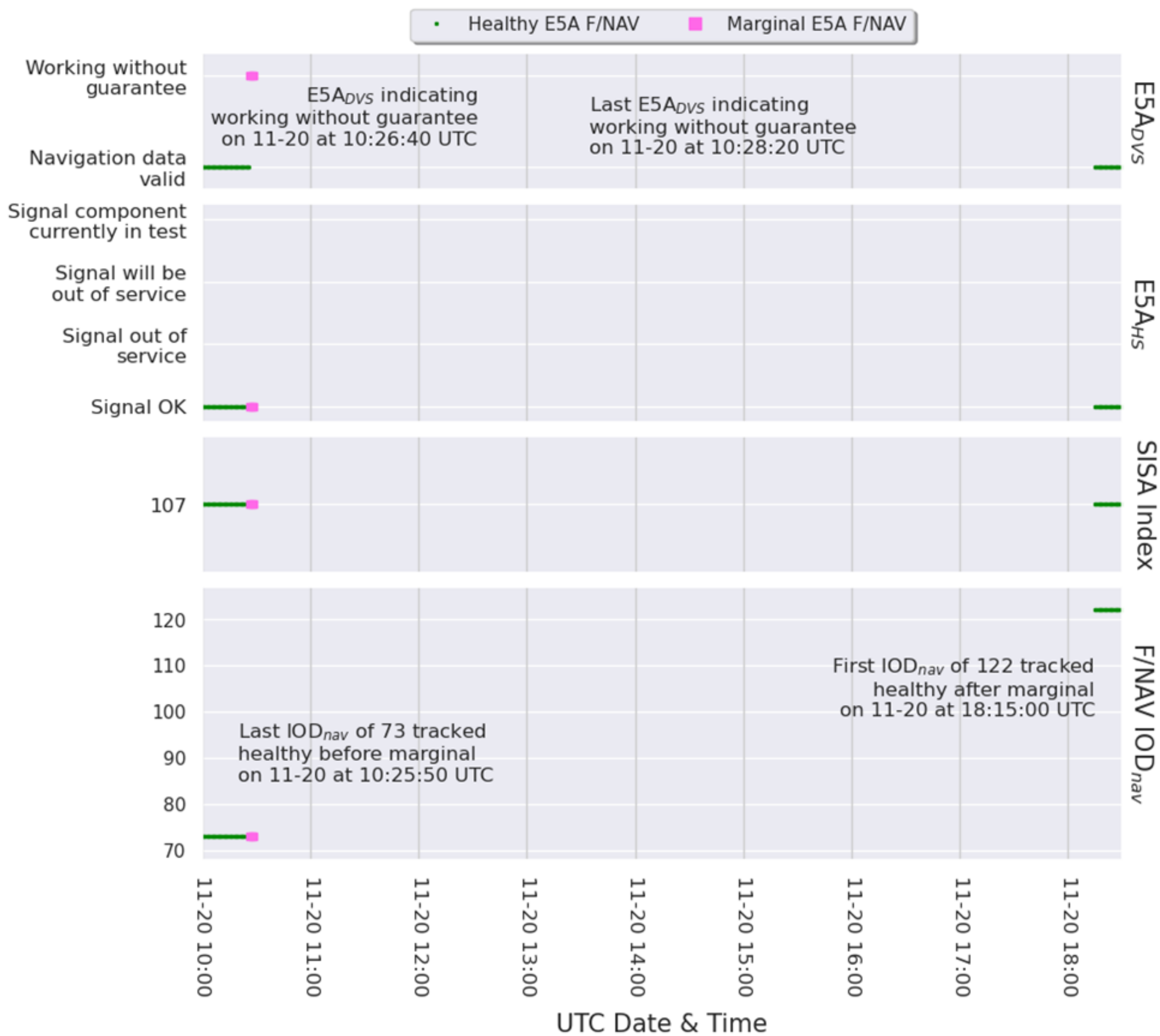


Figure 3-15. Marginal F/NAV Signal (SVID 27 Tracked at WJHTC November 20)

3.1.2.12 SVID 4 December 11, 2023

On December 11 at 13:39:10 the NovAtel G-III receiver at the WJHTC first detected a marginal E5a signal due to the E5A DVS signal indicating working without guarantee in the F/NAV subframe with IOD_{nav} 96. The signal was last seen healthy on December 11 at 13:38:20 with F/NAV subframe IOD_{nav} 96 and first seen to return to a healthy state on December 11 at 14:31:40 with F/NAV subframe IOD_{nav} 102 (see Figure 3-16).

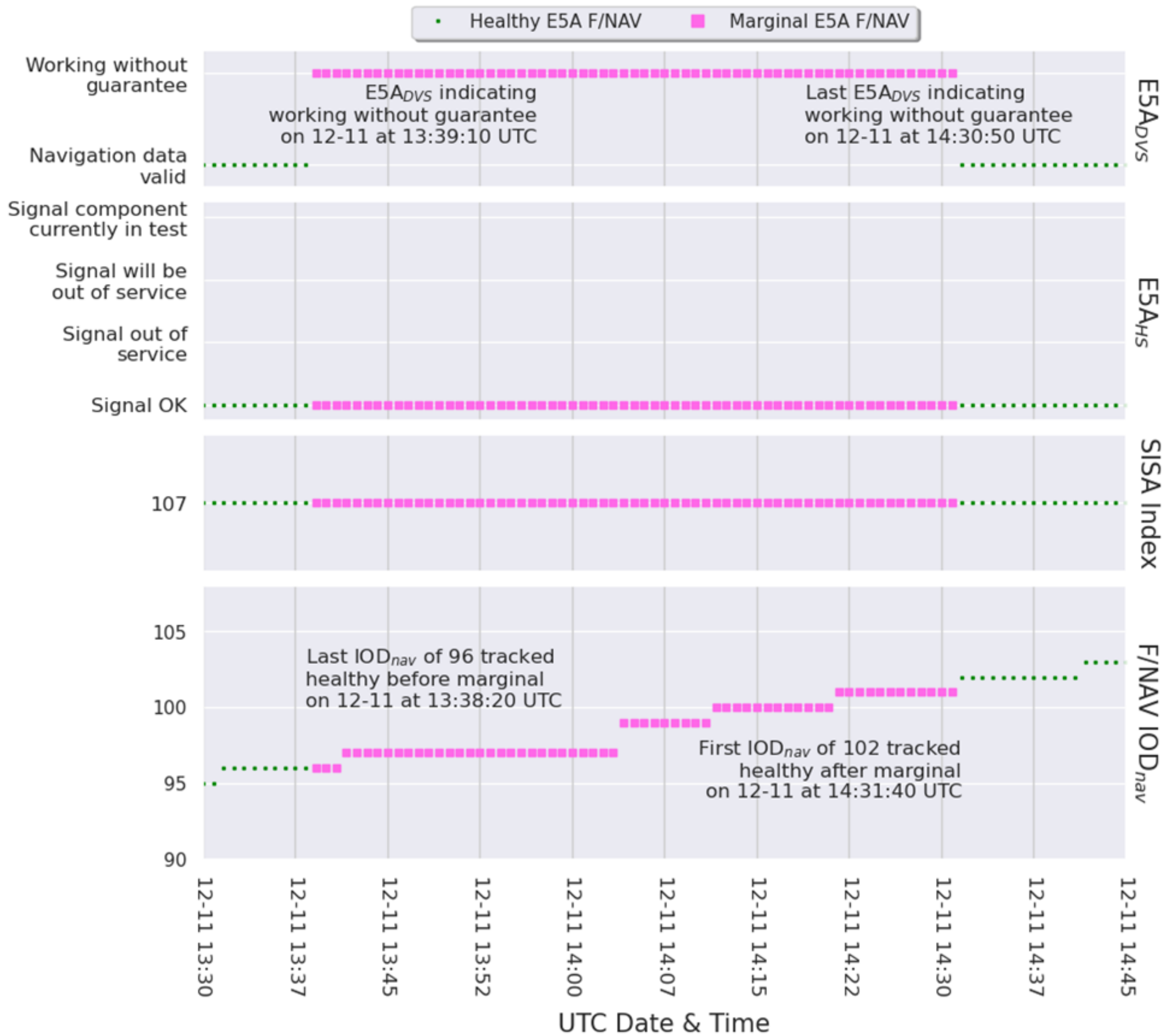


Figure 3-16. Marginal F/NAV Signal (SVID 4 Tracked at WJHTC December 11)

3.2 Satellite Position Errors

3.2.1 SIS Ranging Accuracy

This section is planned for future reports. It will present the SIS ranging accuracy for each individual satellite as well as the SIS ranging accuracy over all satellites to evaluate the MPLs as described in OS SDD v1.2, Section 3.3, Tables 9 and 10.

3.2.1.1 Data Source and Rate

The offline analysis in this report plans to use two sources of input data: Galileo broadcast navigation data and post-processed precise data. The broadcast navigation data consists of satellite orbit and clock parameters. The precise data consists of Galileo orbit and clock parameters. It is used as the truth reference.

A subset of the Galileo broadcast navigation data is available from the IGS in Receiver Independent Exchange (RINEX) navigation file format [6]. The available subset of broadcast navigation data will be evaluated to determine if the Broadcast Group Delay term can be included in the error models. Precise Galileo ephemerides and clock are generated from CODE in the Standard Product #3 (SP3) format [7, 8].

3.2.1.2 Data Collection and Cleansing

A customized tool is used to automate the data downloads on a daily basis. All data are protected by checksums and other basic integrity checks. Galileo broadcast navigation data are downloaded from the Crustal Dynamics Data Information System (CDDIS) [9] archive site. Precise Multi-GNSS Experiment (MGEX) data are downloaded from the CDDIS archive server.

The broadcast navigation data, as received in RINEX format from IGS, sometimes contains defects such as duplications, inconsistencies, discrepancies, and errors that can cause false anomalies. A cleansing algorithm is applied to the IGS data to generate “validated” navigation messages, which have as many of these defects removed as possible. This process is based on the algorithm described by Heng [10].

3.2.1.3 Error Computation

For each timestep when precise data are available, all valid broadcast navigation data over all age of data (AOD) are used to propagate the satellite orbits and clocks. To account for clock offset in the precise product, at each epoch, the clock residuals between healthy precise and broadcast products are filtered for outliers, then a mean correction is applied onto the CODE precise clock estimate. At each data point for which both sources indicate a healthy signal and valid data within the fit interval, the satellite position error is determined by calculating the difference between the CODE-derived reference value and the calculated, propagated satellite position, in Earth-Centered, Earth-Fixed (ECEF) coordinates. The errors are segregated into radial, along-track, and cross-track (RAC) errors. The satellite position error is computed geometrically at each epoch to produce the maximum projected error (MPE) and projected along the lines of sight to individual user locations on Earth to produce User Projected Error (UPE). MPE and UPE are two forms of signal-in-space range error (SISRE) that are used to evaluate the error distributions [10].

UPE will be calculated using 200 evenly distributed user locations around the globe. This density has been determined to be sufficient such that a value within 2 cm of the unfaulted MPE will be observed at one or more of the user locations [11]. MPE will be computed for each satellite, at each epoch. UPE will be computed for each of the 200 user locations, for each satellite in view, for each epoch. A mask angle of 5 degrees is used for MPE and UPE computations. Figure 3-17 shows the 200 user locations. The UPE at these points and the MPE will be used to evaluate the SIS ranging accuracy as described in OS SDD v1.2, Section 3.3, Tables 9 and 10.

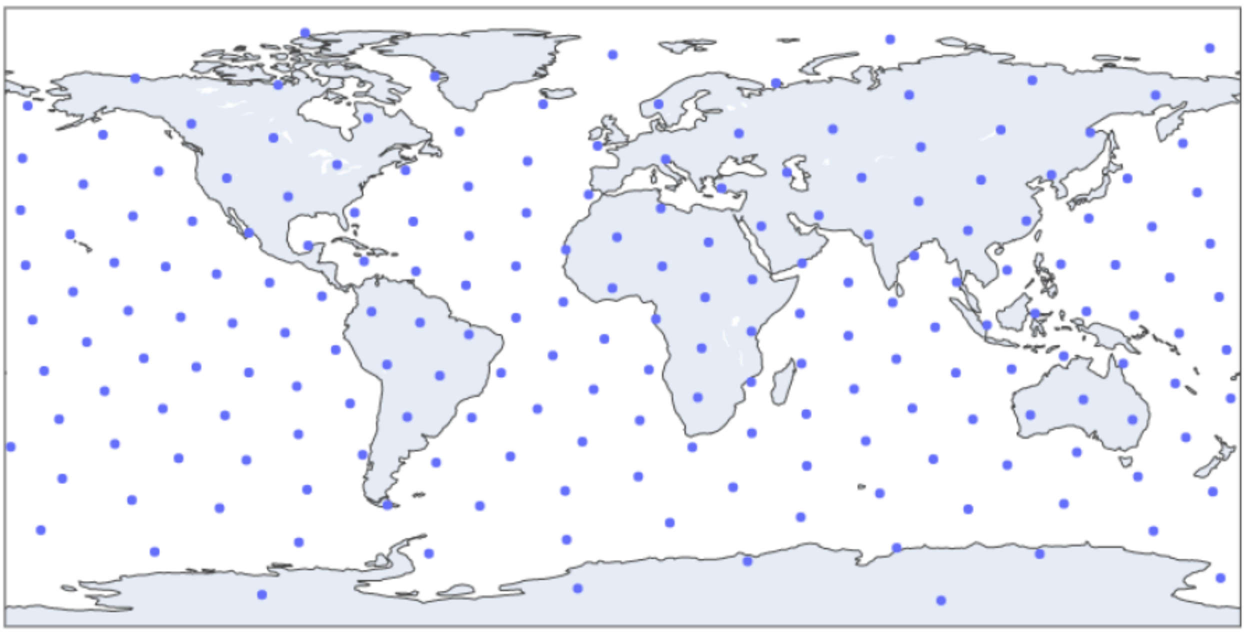


Figure 3-17. The 200 User Locations

3.2.2 SIS Ranging Accuracy Quarterly Results

Figures in this section will present the SIS ranging accuracy for each individual satellite as well as the SIS ranging accuracy over all satellites.

This section is planned for future reports.

4. GALILEO TIME TRANSFER PERFORMANCE

The Galileo time transfer error analysis will be provided in future reports.

4.1 Availability

The availability of the Galileo UTC Time Dissemination Service is defined as the percentage of time that the system provides at least one "healthy" ranging/timing SIS above a minimum elevation angle of 5 degrees.

4.2 Accuracy

The Galileo SIS UTC Time Dissemination Accuracy and the Galileo SIS UTC Frequency Dissemination Accuracy are computed as the daily average error of the normalized time and frequency offset relative to UTC for a user equipped with a Standard Timing/Calibration Laboratory Receiver.

The accuracy data is planned to be obtained from the U.S. Naval Observatory (USNO) website [12]. The data file will contain daily overall values for the entire constellation. They will be an estimate of the difference between the USNO Master Clock and Galileo System Time (GST). These values will represent a 2-day filtered linear solution and be computed for 0 hours Universal Time (UT) of the second day and published daily for the preceding day. To evaluate the Galileo time-transfer error, the data file will be used to create a histogram to represent the distribution of the Galileo time error. The histogram will be created by taking the absolute value of time difference between the USNO Master Clock and GST, then creating data bins with 1-nanosecond precision. The number of samples in each bin will then be plotted to form a histogram.

5. GALILEO POSITIONING PERFORMANCE

This section of the report provides information and performance for the availability of Galileo Position Service and Galileo Position Accuracy.

5.1 Availability of the Galileo Positioning Service

Figures in this section show the availability of positioning at the worst user location (WUL) and average user location (AUL) to assess the commitments to the MPLs described in OS SDD v1.2, Section 3.4.4, Table 16 and 17. Sections 3.2.1–3.2.2 describe the data source and processing followed to arrive at the SISRE. The SISRE, along with the DOP described in Section 2, are used to derive the position accuracy in this section as described in OS SDD v1.2, Section C.4.5.3.

5.2 Galileo Position Accuracy

Galileo user position errors are not specified in the Galileo OS SDD. The data that pertains to this section is assessed as monthly statistics to coincide with the MPL conditions defined in the OS SDD for Availability of Galileo Position Service (see Section 5.1).

Galileo navigation measurement data is being collected using two G-III receivers located at the WJHTC and a GT7800 receiver located in Elko, Nevada to process Galileo position accuracy. The Galileo user position tool uses a dual-frequency solution processing the E1b–E5a frequencies (F/NAV message). The user position is calculated once per second and compared to the surveyed position of the receiver to assess the position error when PDOP is less than or equal to 6. Galileo satellite measurement data is used in the position solution according to the ephemeris and SIS health status specifications in the OS SDD. The FAA Satellite Navigation Branch is currently working to incorporate and validate other test receivers processing Galileo navigation and measurement data into this report.

Navigation error data, collected from the two G-III receivers and the GT7800 receiver, was processed to determine position accuracy at each location. This was done using the user position tool described above. Position errors were analyzed, and statistics were generated to produce histogram data and daily 95% trends of the position errors. Figure 5-1 through Figure 5-6 show distribution of the calculated horizontal position error (HPE) and vertical position error (VPE) for the receivers over a 1-month period, highlighting the 95th percentile. Figure 5-7 shows the daily 95% horizontal and vertical position errors.

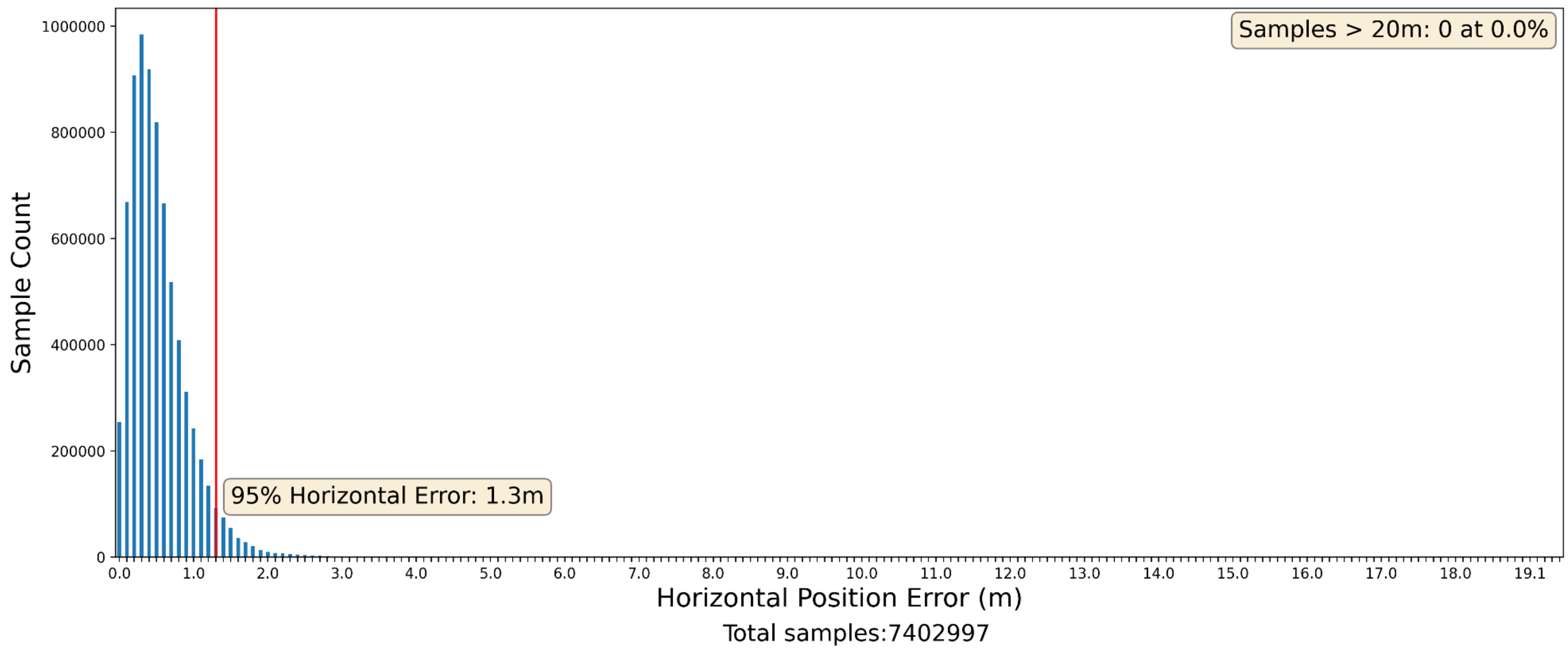


Figure 5-1. 95% Horizontal Error—October 2023

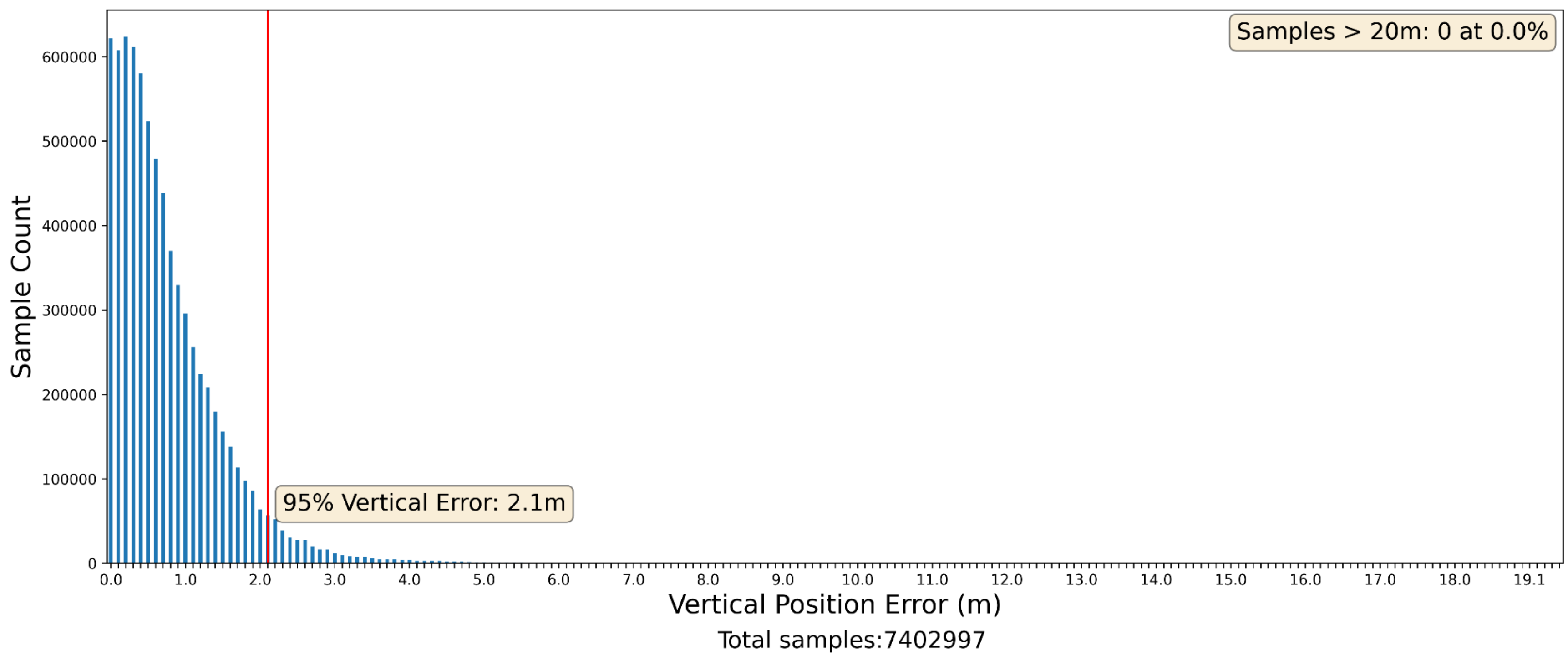


Figure 5-2. 95% Vertical Error—October 2023

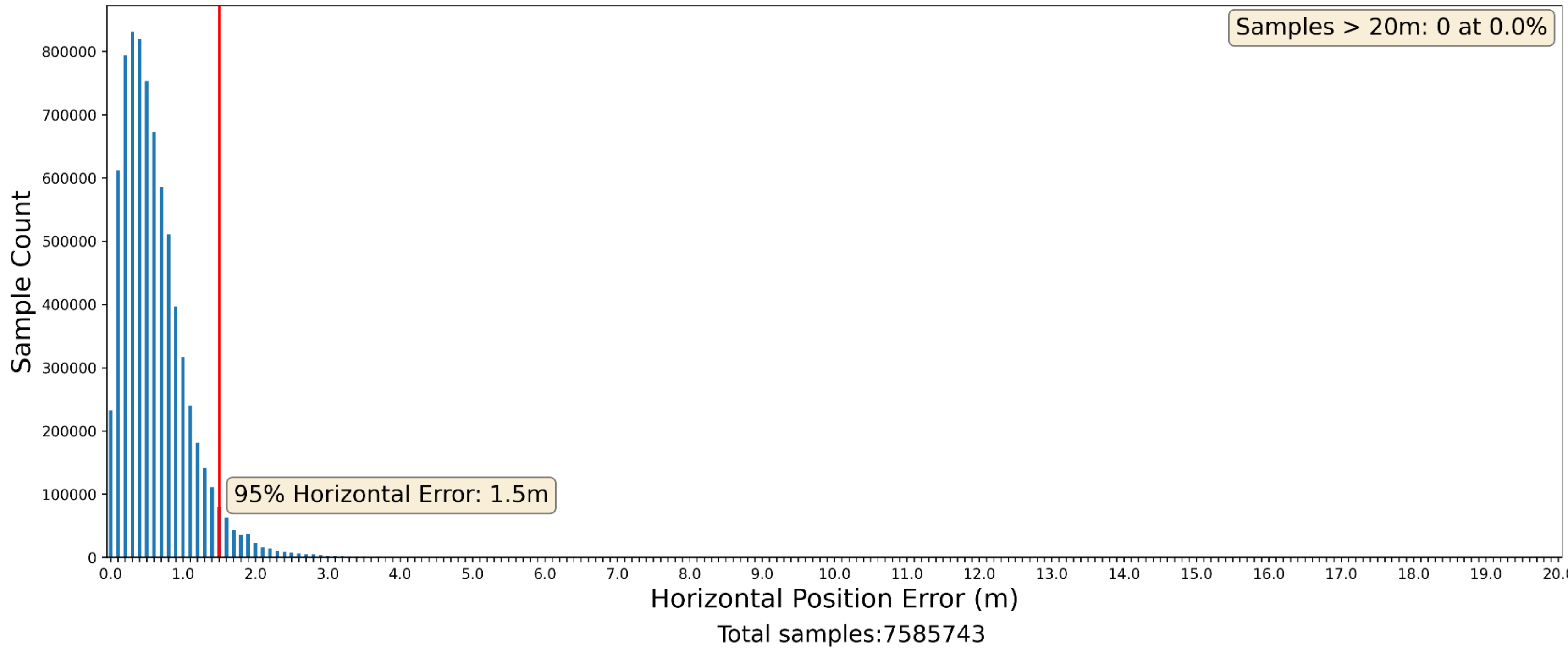


Figure 5-3. 95% Horizontal Error—November 2023

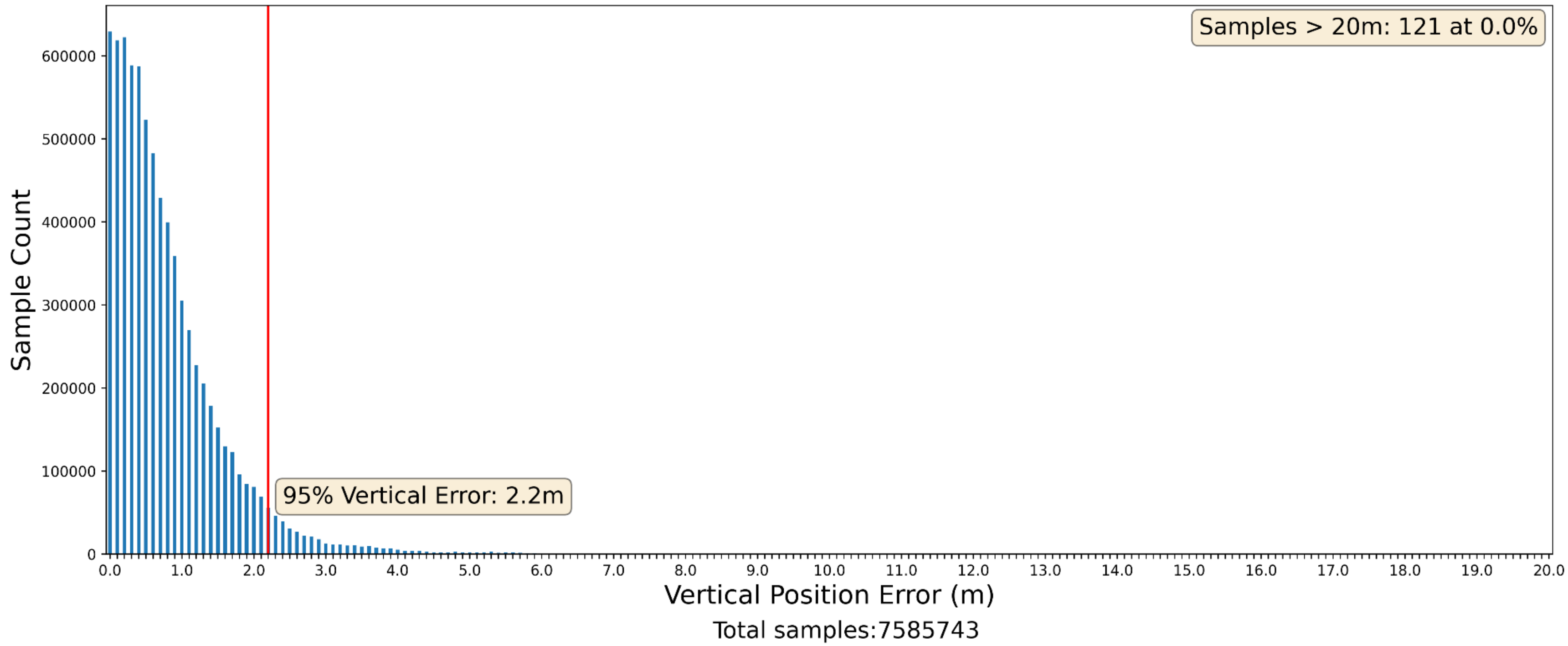


Figure 5-4. 95% Vertical Error—November 2023

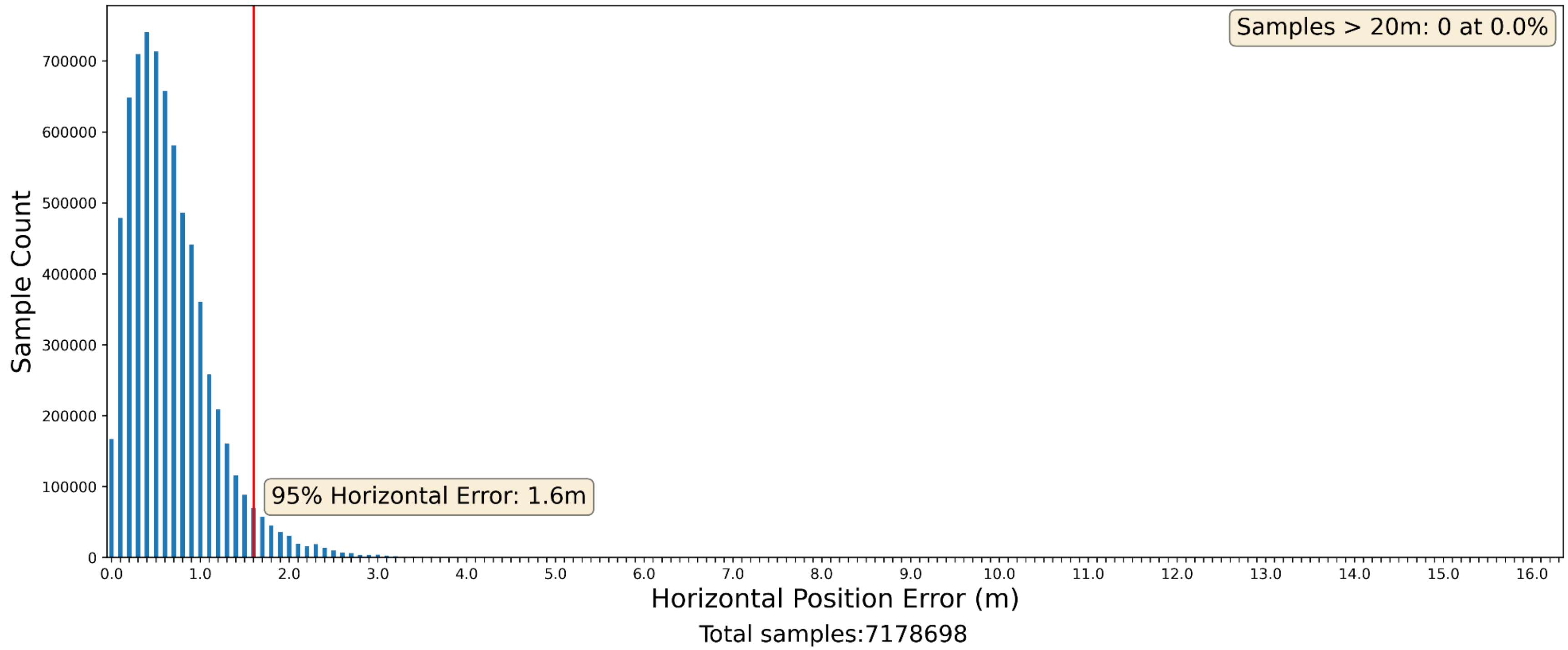


Figure 5-5. 95% Horizontal Error—December 2023

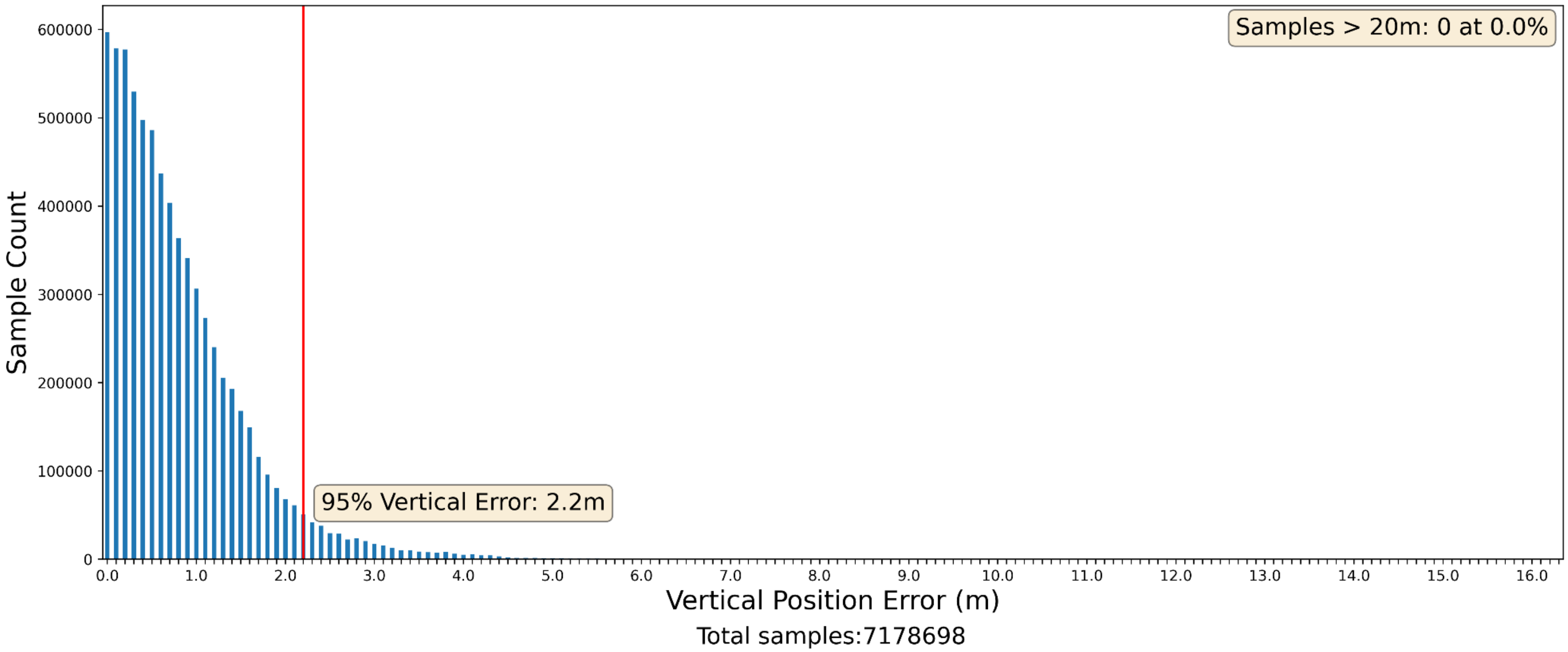


Figure 5-6. 95% Vertical Error—December 2023

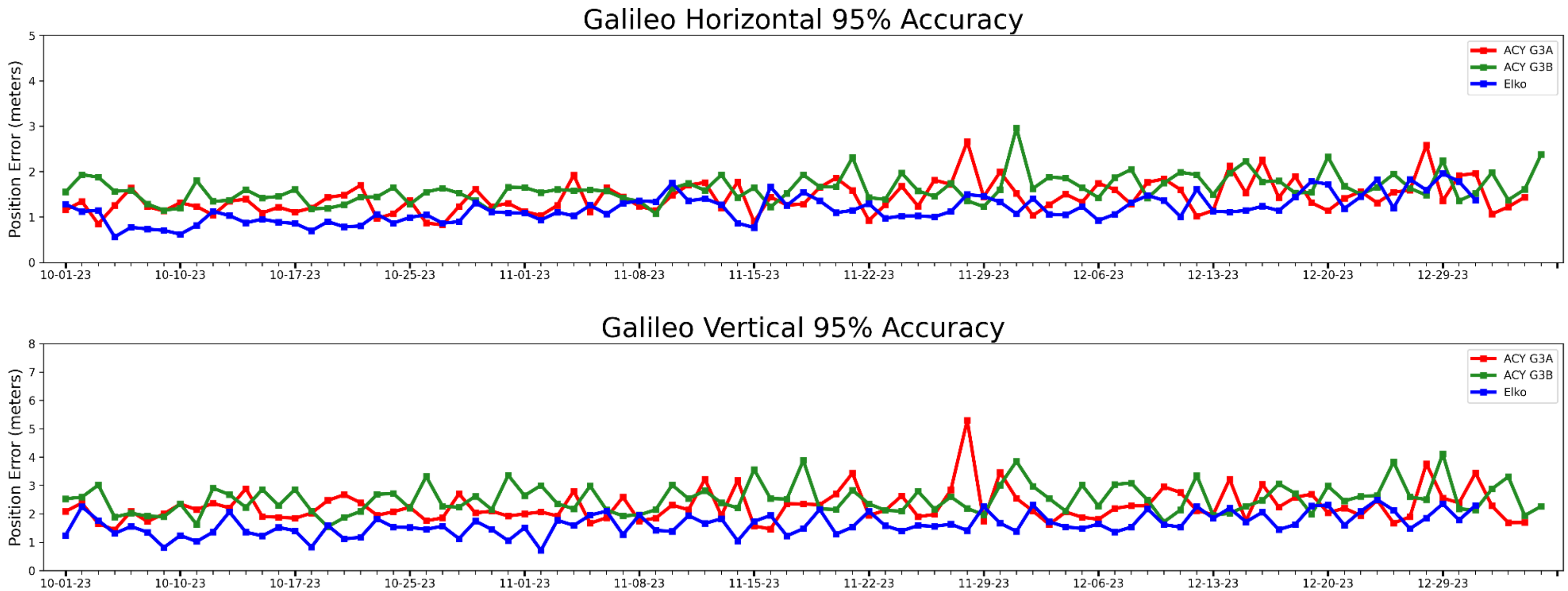


Figure 5-7. 95% Horizontal and Vertical Trends—2023 Q4

5.3 IGS Data (Position Errors)

This section will be included in future reports.

6. TIMELY PUBLICATION OF NAGUS

The Galileo OS SDD v1.2, Section 3.6.1 [2] discusses the timely publication of NAGUs. A published NAGU is considered timely if it fulfills two criteria: 1) if a NAGU is categorized as planned, it must be published over 48 hours before the event occurs, and 2) if a NAGU is categorized as unplanned, it must be published within 30 hours of the event that occurred. Table 6-1 provides the MPL of the Timely Publication of NAGUs.

Table 6-1. MPL of the Timely Publication of NAGUs

MPL OF THE TIMELY PUBLICATION OF NAGUS	CONDITIONS AND CONSTRAINTS
For scheduled events affecting the service • ≥48 hours before the service is affected	• Including planned NAGUs • Including GENERAL (LEAP_SECOND) and GENERAL (TIMING PLN_OUTAGE) NAGUs • For GENERAL (NOTICE) NAGUs, planned/unplanned status depends on the nature of the event notified
For general events and unscheduled outages or events affecting the service • ≤30 hours after the event affecting the service is detected	• Including Unplanned NAGUs • Including CANCEL, RESCH, EXTNS NAGUs • Including Service Availability NAGUs • Including all General NAGUs, with the exception of GENERAL (LEAP SECOND) and GENERAL (TIMING PLN_OUTAGE) • For GENERAL (NOTICE) NAGUs, planned/unplanned status depends on the nature of the event notified

Satellite availability performance was analyzed based on published NAGUs. During this reporting period, October 1 through December 31, 2023, five NAGUs were published. Two NAGUs forecasted satellite positioning outages, and there were two USABLE NAGUs. Of the five published NAGUs, all five met the timeliness standards defined in the SDD. A complete list of NAGUs for the reporting period is provided in Table 6-7.

Table 6-2 provides a summary of the time each NAGU affected positioning service. Total Unscheduled time is the amount of time in hours a NAGU indicated service outages without notifying Galileo users in advance or that fell outside the forecasted outage time. Total Scheduled time is the actual time in hours that satellite outages affected service according to the USABLE NAGU within the forecasted time indicated in the corresponding PLN_OUTAGE NAGU. The Total time is the amount of time, both unscheduled and scheduled, that a satellite outage affected service.

Table 6-2. NAGUs Affecting Satellite Positioning Availability

NAGU	SV ID	Type	Start	End	Total Unscheduled (hrs)	Total Scheduled (hrs)	Total (hrs)
2023055	05	USABLE	Nov 07, 2023, 06:15 UTC	Nov 16, 2023, 18:05 UTC	0.00	227.83	227.83
2023057	04	USABLE	Dec 11, 2023, 13:39 UTC	Dec 11, 2023, 14:31 UTC	0.00	0.86	0.86
Totals of Unscheduled, Scheduled, and Total Downtime					0.00	228.69	228.69

Table 6-3 provides a summary of published NAGUs that forecast satellite outages. “EXTNS” NAGUs are listed in the table, but they are not included in the Total Forecasted Downtime statistic.

Table 6-3. NAGUs Forecasted to Affect Satellite Positioning Availability

NAGU	SV ID	TYPE	Start	End	Total (hrs)	Comments
2023054	05	PLN_MANV	Nov 07, 2023, 05:00 UTC	Nov 16, 2023, 20:50 UTC	231.83	2023055
2023056	04	PLN_OUTAGE	Dec 11, 2023, 13:25 UTC	Dec 11, 2023, 14:55 UTC	1.50	2023057
Total Hours					233.33	

Table 6-4 provides a summary of the time each NAGU affected GGTO service. Total Unscheduled time is the amount of time in hours that a NAGU indicated service outages without notifying Galileo users in advance or that fell outside the forecasted outage time. Total Scheduled time is the actual time in hours that satellite outages affected service according to the TIMING USABLE NAGU within the forecasted time indicated in the corresponding PLN_OUTAGE NAGU. The Total time is the amount of time, both unscheduled and scheduled, that a satellite outage affected service.

Table 6-4. NAGUs Affecting Satellite GGTO Availability

NAGU	SV ID	Type	Start	End	Total Unscheduled (hrs)	Total Scheduled (hrs)	Total
No GGTO Availability Outages							

Table 6-5 provides a summary of published NAGUs that forecast satellite GGTO outages.

Table 6-5. NAGUs Forecasted to Affect Satellite GGTO Availability

NAGU	SV ID	TYPE	Start	End	Total	Comments
No Forecasted GGTO Outages						

Table 6-6 provides a summary of Satellite Reliability, Maintainability, and Availability data, which is collected based on published NAGUs. The Percent Operational was calculated based on the ratio of total actual operating hours to total available operating hours for every satellite according to published NAGUs.

Table 6-6. Galileo Satellite Maintenance Statistics

Satellite Availability Parameter	Positioning	GGTO
Total Forecasted Downtime (hrs)	233.33	0
Total Actual Downtime (hrs)	228.69	0.00
Total Actual Scheduled Downtime (hrs)	228.69	0
Total Actual Unscheduled Downtime (hrs)	0	0.00
Total Satellite Outages	2	0
Scheduled Satellite Outages	2	0
Unscheduled Satellite Outages	0	0
Percent Operational—Scheduled Downtime (%)	99.55	100
Percent Operational—All Downtime (%)	99.55	100

Table 6-7 provides the timeliness details of each NAGU that occurred during this quarter.

Table 6-7. Summary of 2023 Q4 Published NAGUs

Month	NAGU Type	NAGU Number	Published	Event Time	Category	Timeliness	Description
OCT	GENERAL (HAS UNP_SHTRCVR)	2023053	Oct 15, 2023, 17:00 UTC	Oct 15, 2023, 05:32 UTC	UNPLANNED	NAGU was published 11.47 after the event.	USERS ARE ADVISED OF HAS SERVICE UNAVAILABILITIES OCCURRED DURING THE PERIOD STARTING FROM 2023-10-15 BEGINNING 05:32 UTC UNTIL 2023-10-15 ENDING 07:25 UTC.
NOV	PLN_MANV	2023054	Nov 03, 2023, 11:00 UTC	Nov 07, 2023, 05:00 UTC	PLANNED	NAGU was published 90.00 hours before the event.	GALILEO SATELLITE GSAT0214 (ALL SIGNALS) WILL BE UNAVAILABLE FROM 2023-11-07 BEGINNING 05:00 UTC DUE TO MANOEUVRE. OUTAGE RECOVERY ESTIMATED ON 2023-11-16 20:50 UTC.
	USABLE	2023055	Nov 16, 2023, 19:30 UTC	Nov 16, 2023, 18:05 UTC	UNPLANNED	NAGU was published 1.42 hours after the event.	GALILEO SATELLITE GSAT0214 (ALL SIGNALS) IS USABLE SINCE/AS OF 2023-11-16 BEGINNING 18:05 UTC. PAYLOAD ON PHM CLOCK. GALILEO SATELLITE GSAT0214 (ALL SIGNALS) WAS UNAVAILABLE FROM 2023-11-07 BEGINNING 06:15 UTC.
DEC	PLN_OUTAGE	2023056	Dec 07, 2023, 12:20 UTC	Dec 11, 2023, 13:25 UTC	PLANNED	NAGU was published 97.08 hours before the event.	GALILEO SATELLITE GSAT0213 (ALL SIGNALS) WILL BE UNAVAILABLE FROM 2023-12-11 BEGINNING 13:25 UTC. OUTAGE RECOVERY ESTIMATED ON 2023-12-11 14:55 UTC.
	USABLE	2023057	Dec 11, 2023, 16:00 UTC	Dec 11, 2023, 14:31 UTC	UNPLANNED	NAGU was published 1.48 hours after the event.	GALILEO SATELLITE GSAT0213 (ALL SIGNALS) IS USABLE SINCE/AS OF 2023-12-11 BEGINNING 14:31 UTC. PAYLOAD ON PHM CLOCK. GALILEO SATELLITE GSAT0213 (ALL SIGNALS) WAS UNAVAILABLE FROM 2023-12-11 BEGINNING 13:39 UTC.

7. ACRONYMS

AOD	Age of data
ARAIM	Advanced Receiver Autonomous Integrity Monitoring
AUL	Average user location
CDDIS	Crustal Dynamics Data Information System
CODE	Center for Orbit Determination in Europe
DOP	Dilution of precision
DVS	Data Validity Status
ECEF	Earth-Centered, Earth-Fixed
EU	European Union
EUSPA	European Union Agency for the Space Programme
FAA	Federal Aviation Administration
GGTO	GPS-Galileo Time Offset
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GST	Galileo System Time
HAS	High accuracy service
HDOP	Horizontal dilution of precision
HPE	Horizontal position error
HS	Healthy Status
IGS	International GNSS Service
IOC	Initial operational capability
IOD	Issue of Data
MGEX	Multi-GNSS Experiment
MPE	Maximum projected error
MPL	Minimum performance level
NAGU	Notice Advisory to Galileo Users
NAPA	No Accuracy Prediction Available
OS	Open Service
PDOP	Position dilution of precision
RAC	Radial, along-track, and cross-track
RINEX	Receiver Independent Exchange
SDD	Service Definition Document
SIS	Signal-in-space
SISA	Signal-in-space accuracy
SISRE	Signal-in-space range error
SP3	Standard Product #3
SPS	Standard Positioning Service

SVID	Space Vehicle Identification
UPE	User Projected Error
U.S.	United States
USNO	United States Naval Observatory
UTC	Coordinated Universal Time
UTCOE	UTC offset error
VDOP	Vertical dilution of precision
VPE	Vertical position error
WAAS	Wide Area Augmentation System
WJHTC	William J. Hughes Technical Center
WUL	Worst user location

8. REFERENCES

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3. European Global Navigation Satellite Systems Agency, European GNSS Service Center, "NAGUs (Notice Advisory to Galileo Users)," NAGUs (Notice Advisory to Galileo Users) | European GNSS Service Centre (gsc-europa.eu), last accessed August 29, 2024.

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APPENDIX A: GLOBAL MAXIMUM PDOP TREND

Figure A-1 shows the max PDOP at each timestep from the grid described in Section 2.

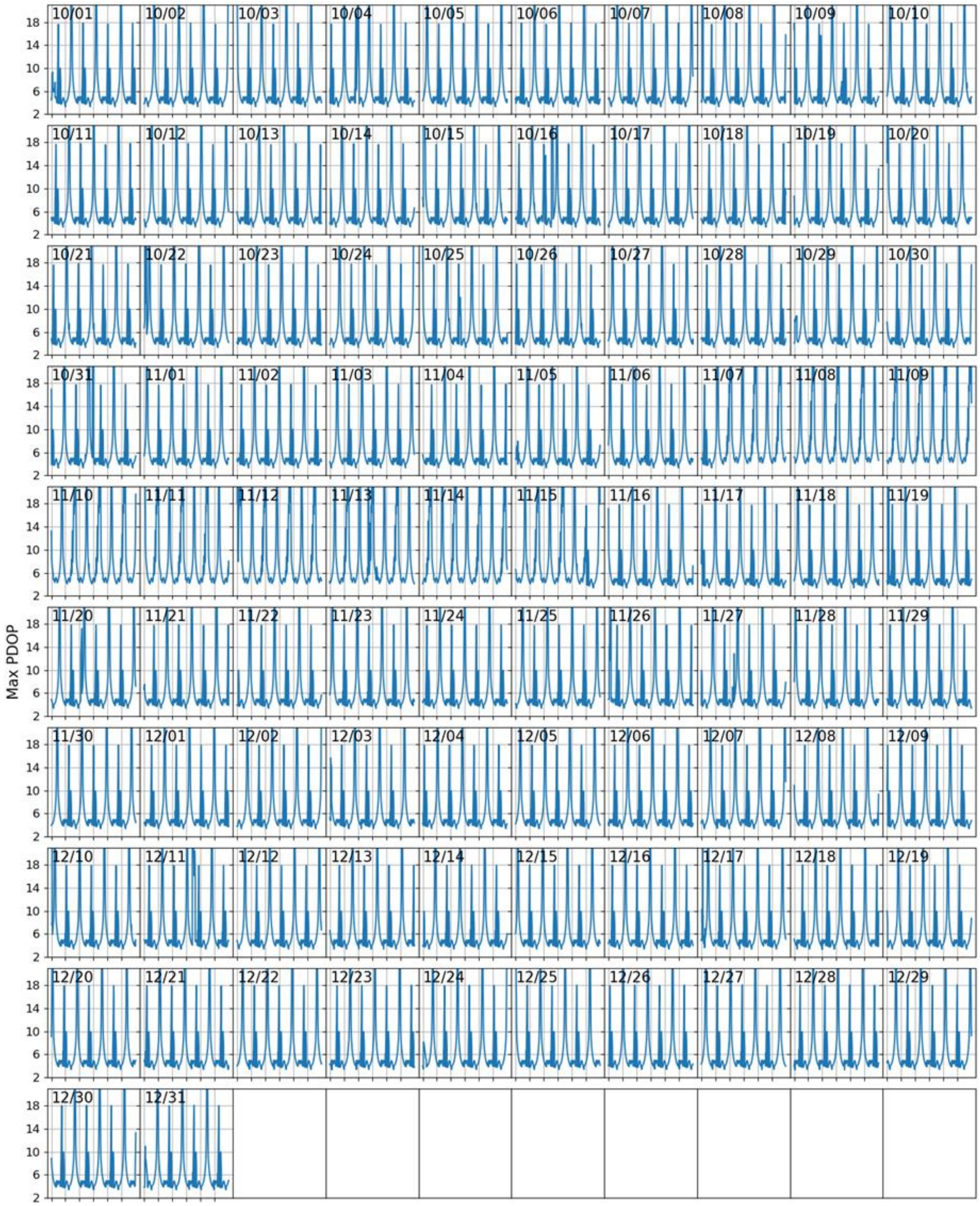

Figure A-1. Global Maximum PDOP Trend

APPENDIX B: GALILEO DAILY MAXIMUM PDOP 10-DAY GEOMETRY CYCLE COMPARISON

Figure B-0-1 through Figure B-0-10 are a group of plots that show the daily maximum PDOP on a 10-day cycle. The Galileo constellation repeats every 10 days, so each set of plots allows easy comparison of PDOP when the constellation geometry is the same. The colors on the plots denote the maximum PDOP seen on that day at that location. The scale for the colors runs from a PDOP of 1 (blue) to 10 (dark red).

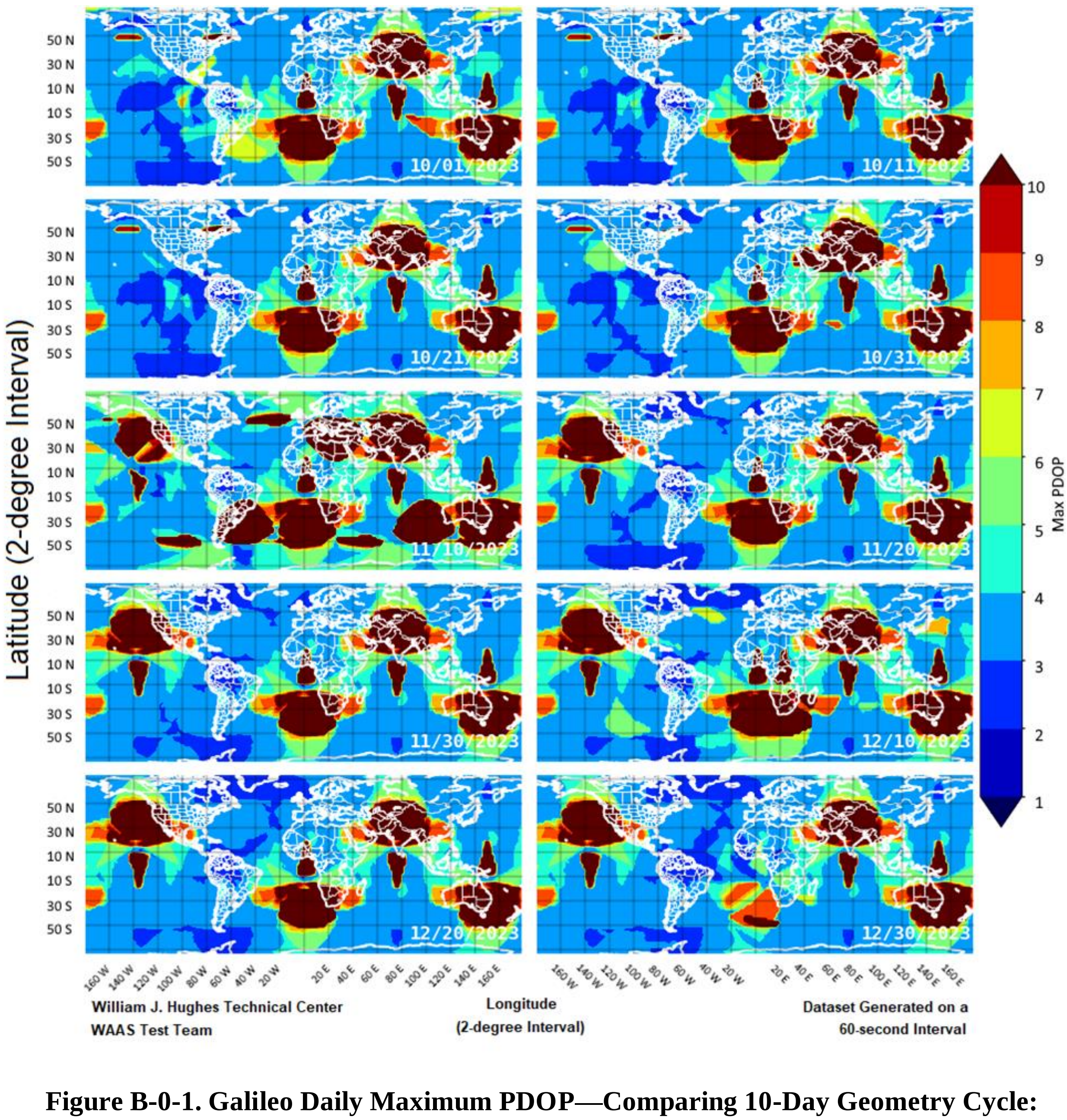

Figure B-0-1. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 1, 2023–December 30, 2023

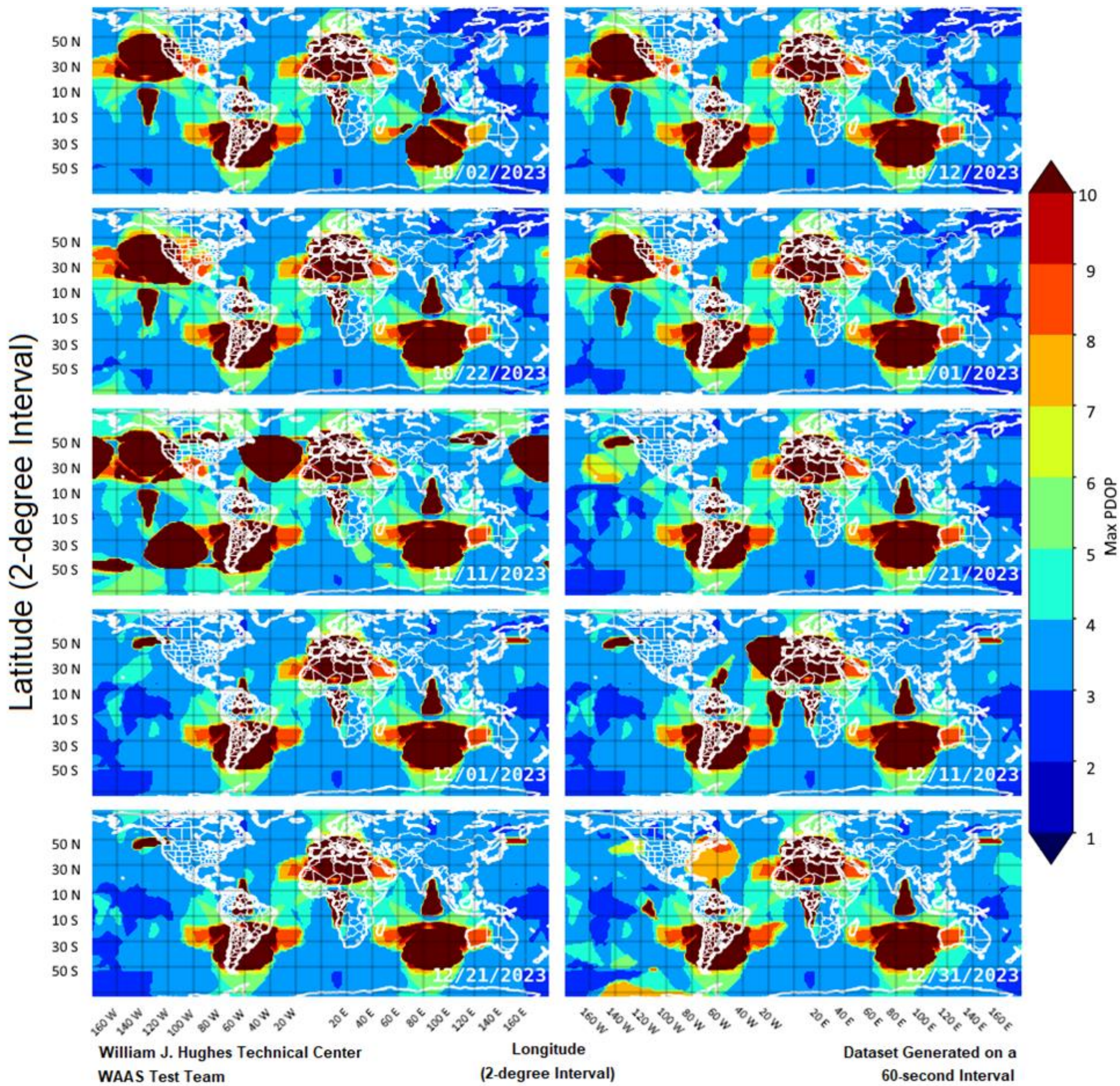

Figure B-0-2. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 2, 2023–December 31, 2023

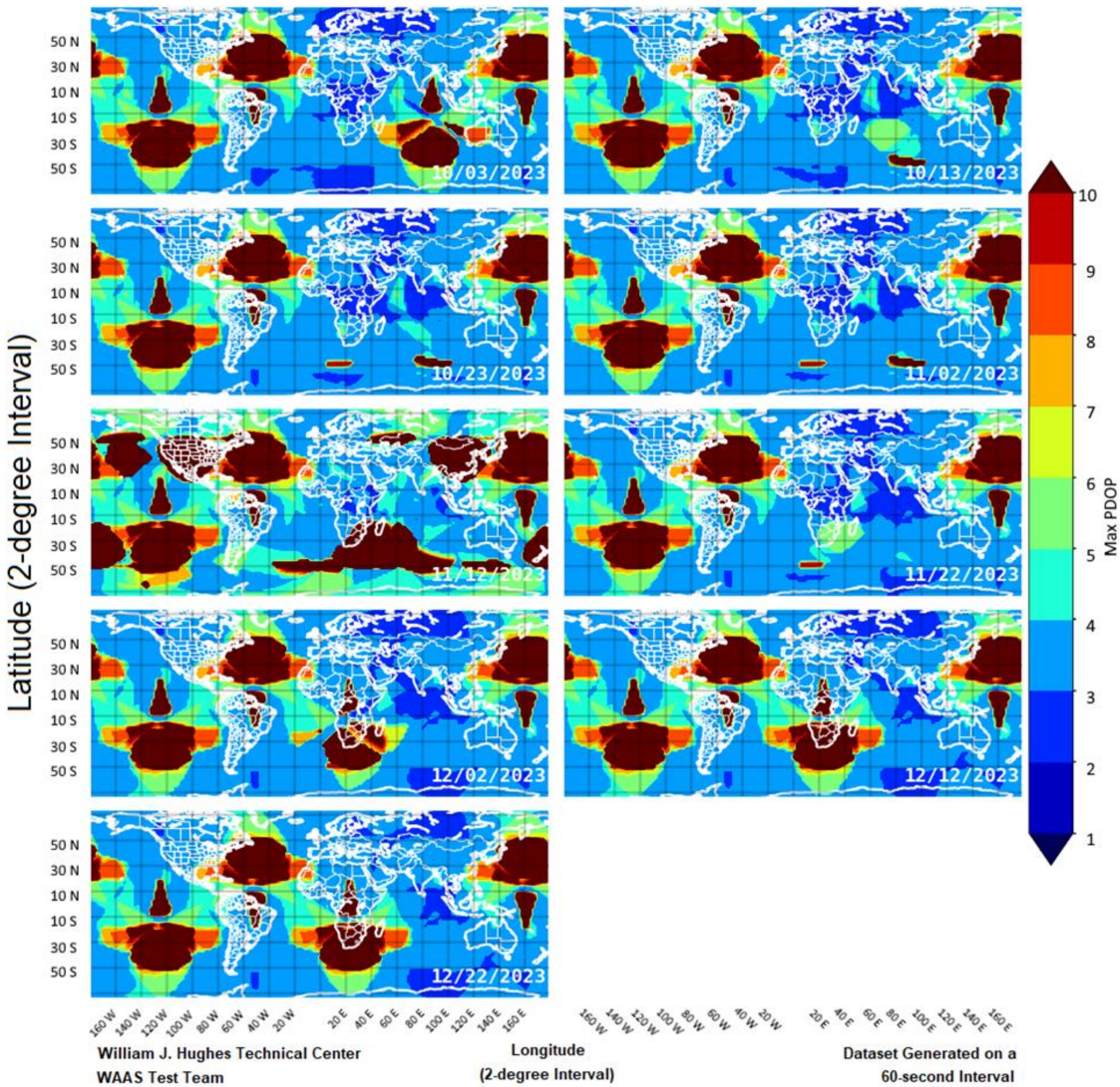

Figure B-0-3. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 3, 2023–December 22, 2023

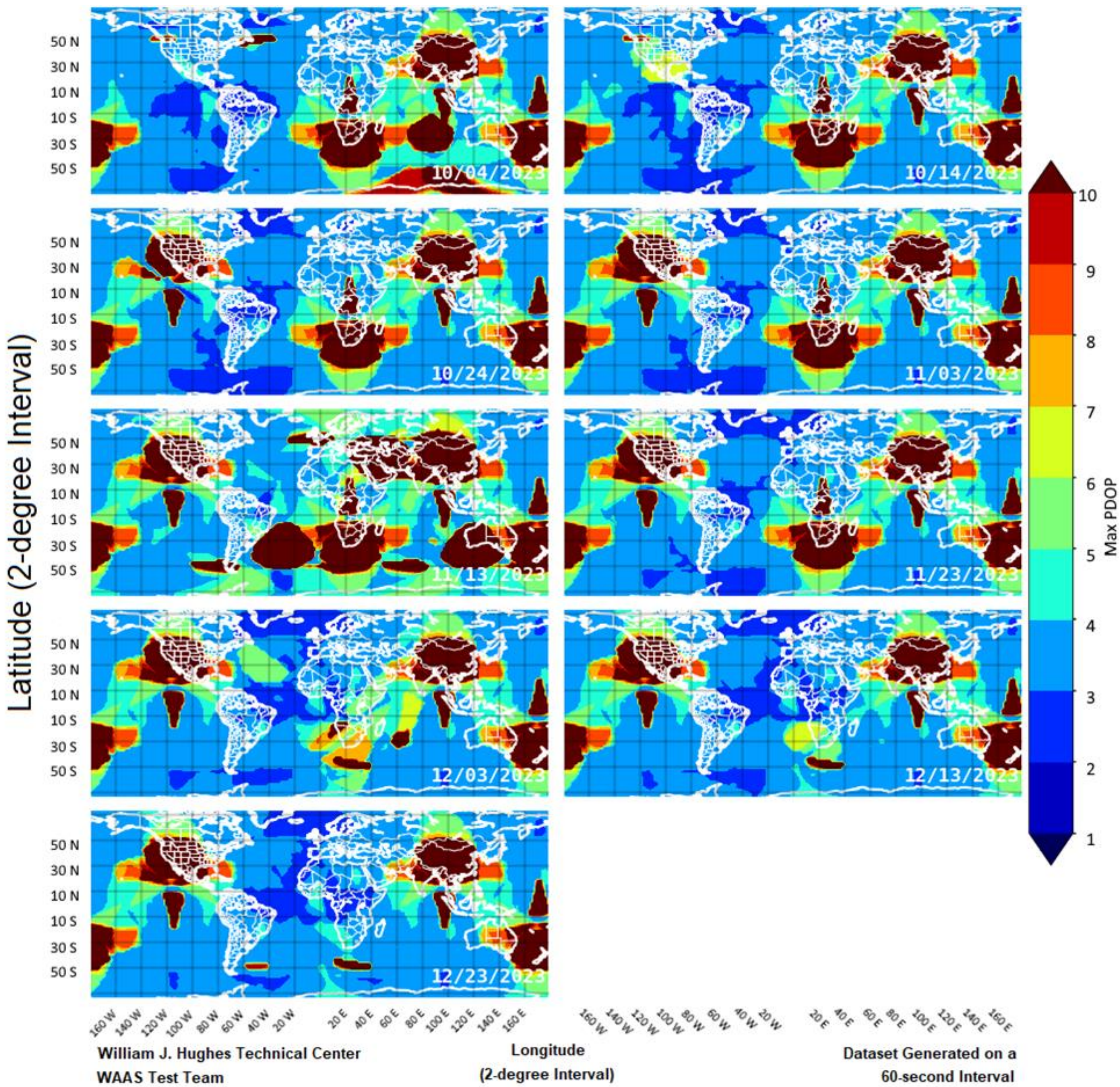

Figure B-0-4. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 4, 2023–December 23, 2023

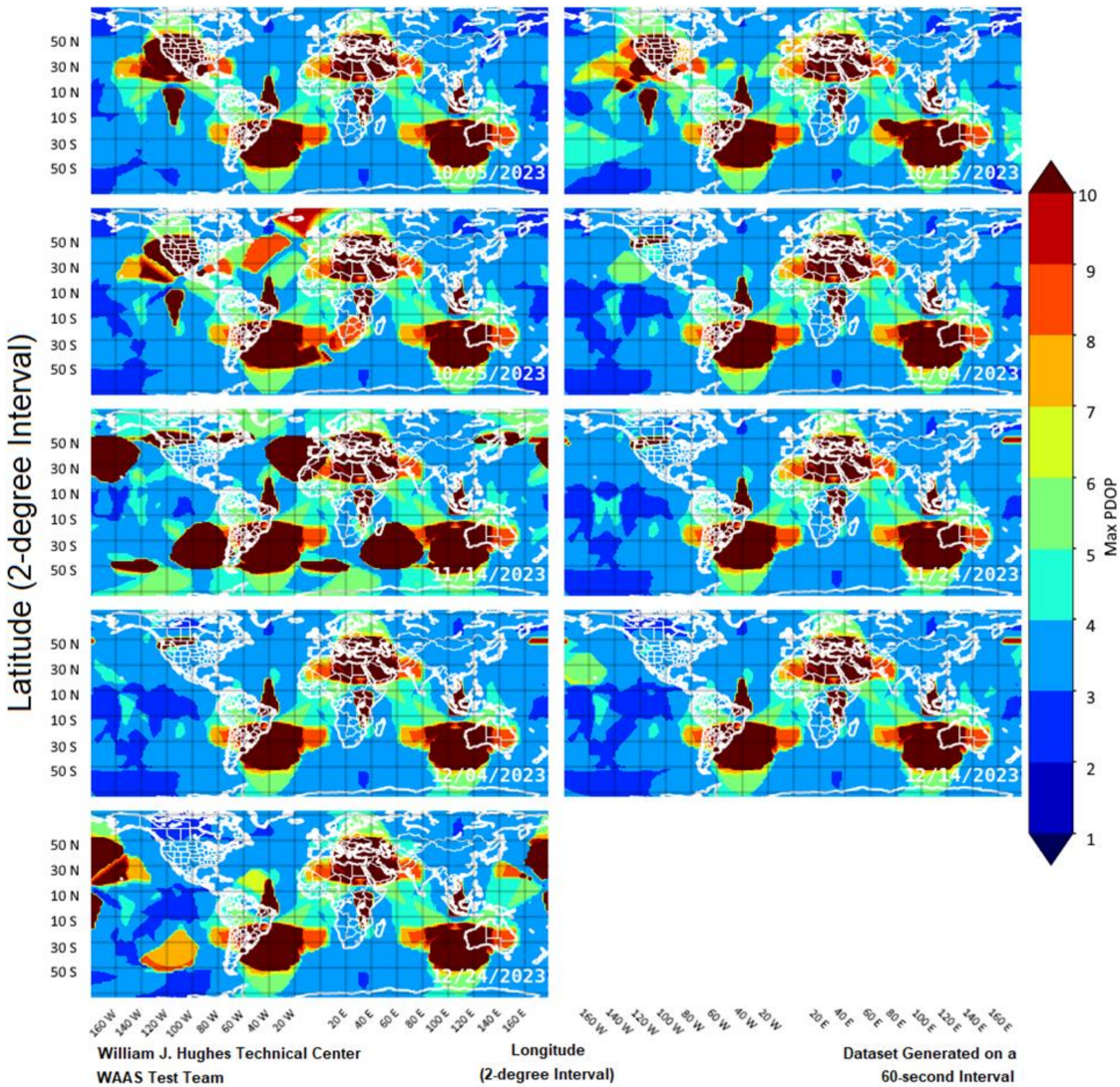

Figure B-0-5. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 5, 2023–December 24, 2023

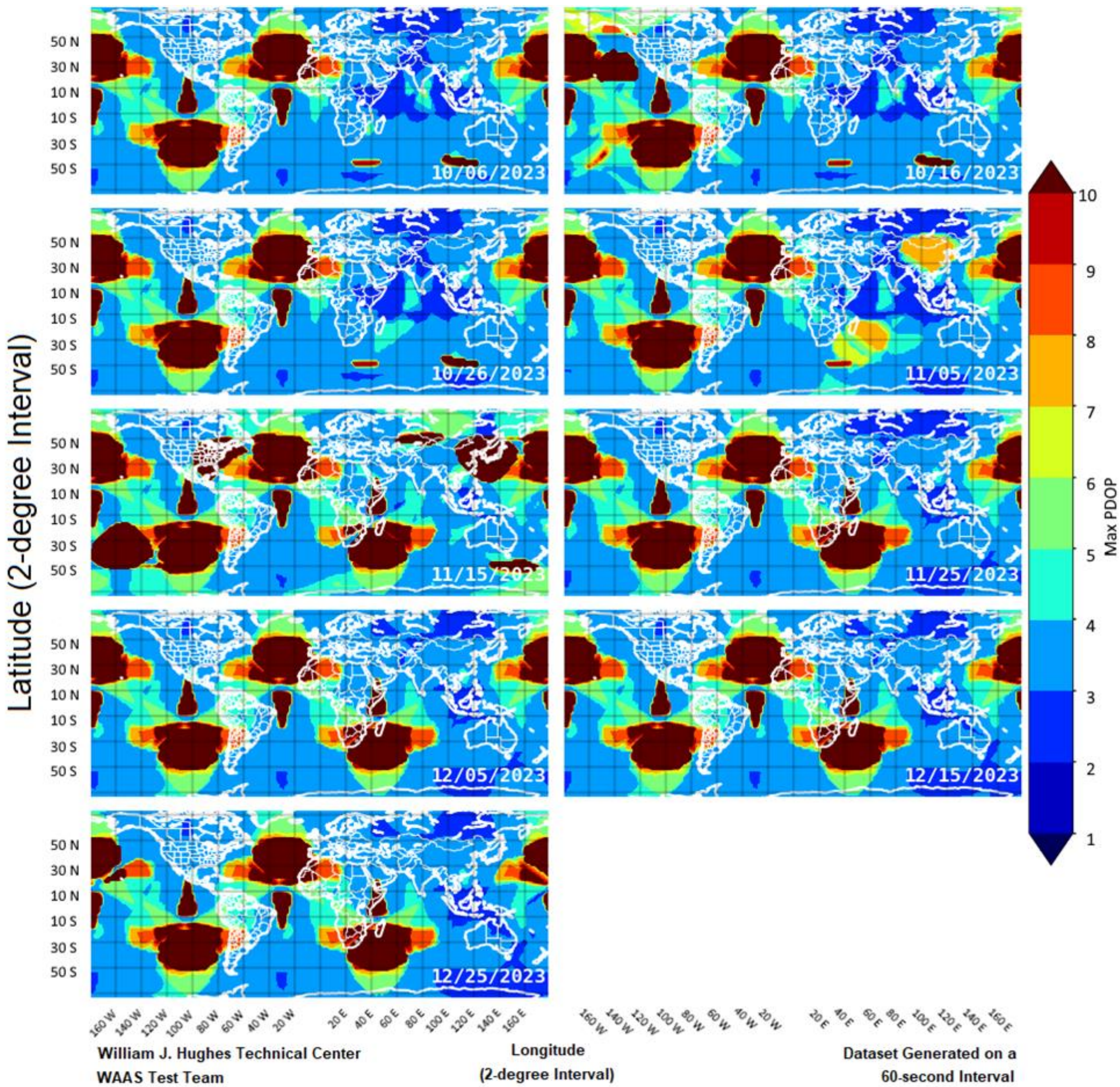

Figure B-0-6. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 6, 2023–December 25, 2023

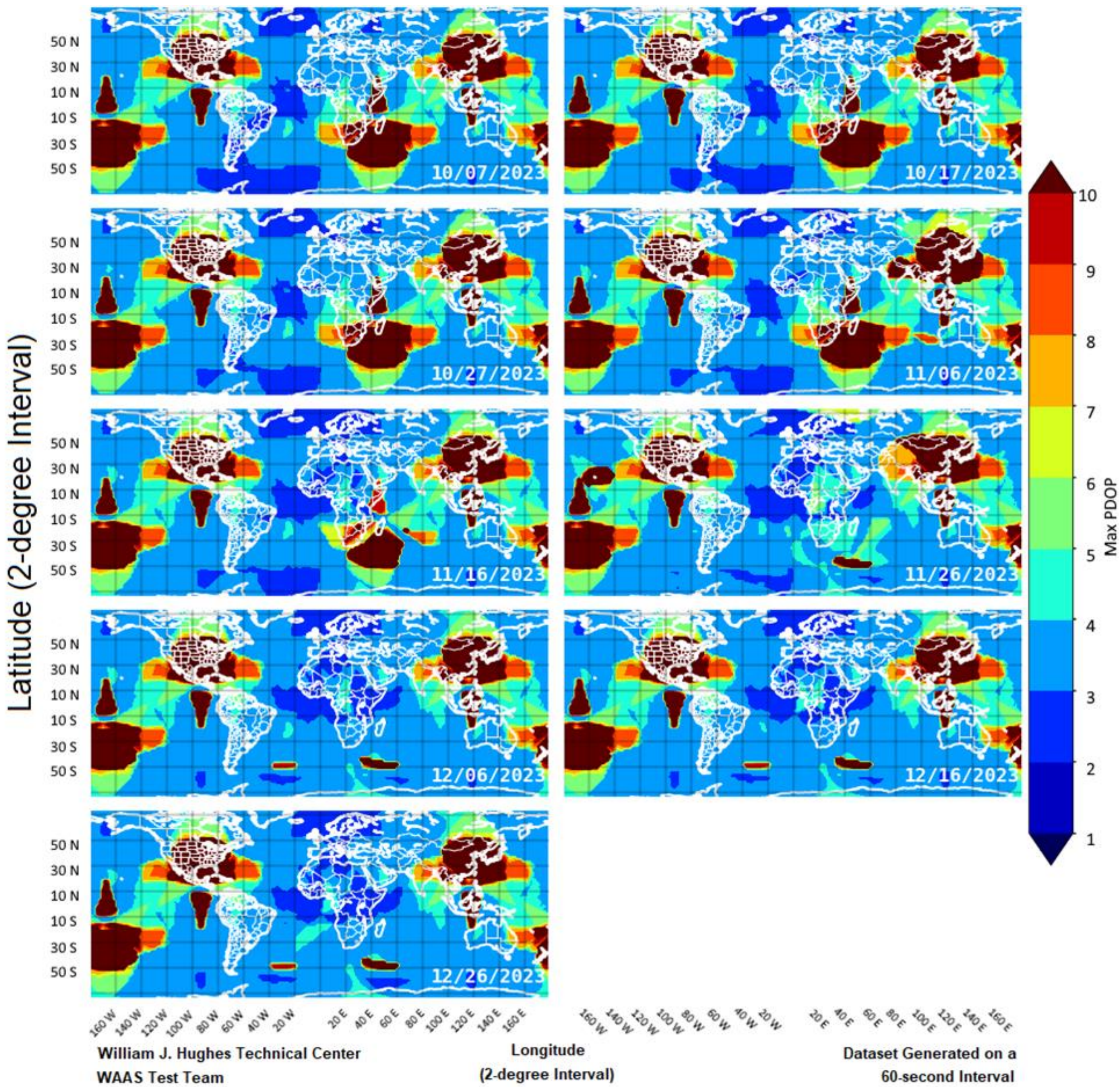

Figure B-0-7. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 7, 2023–December 26, 2023

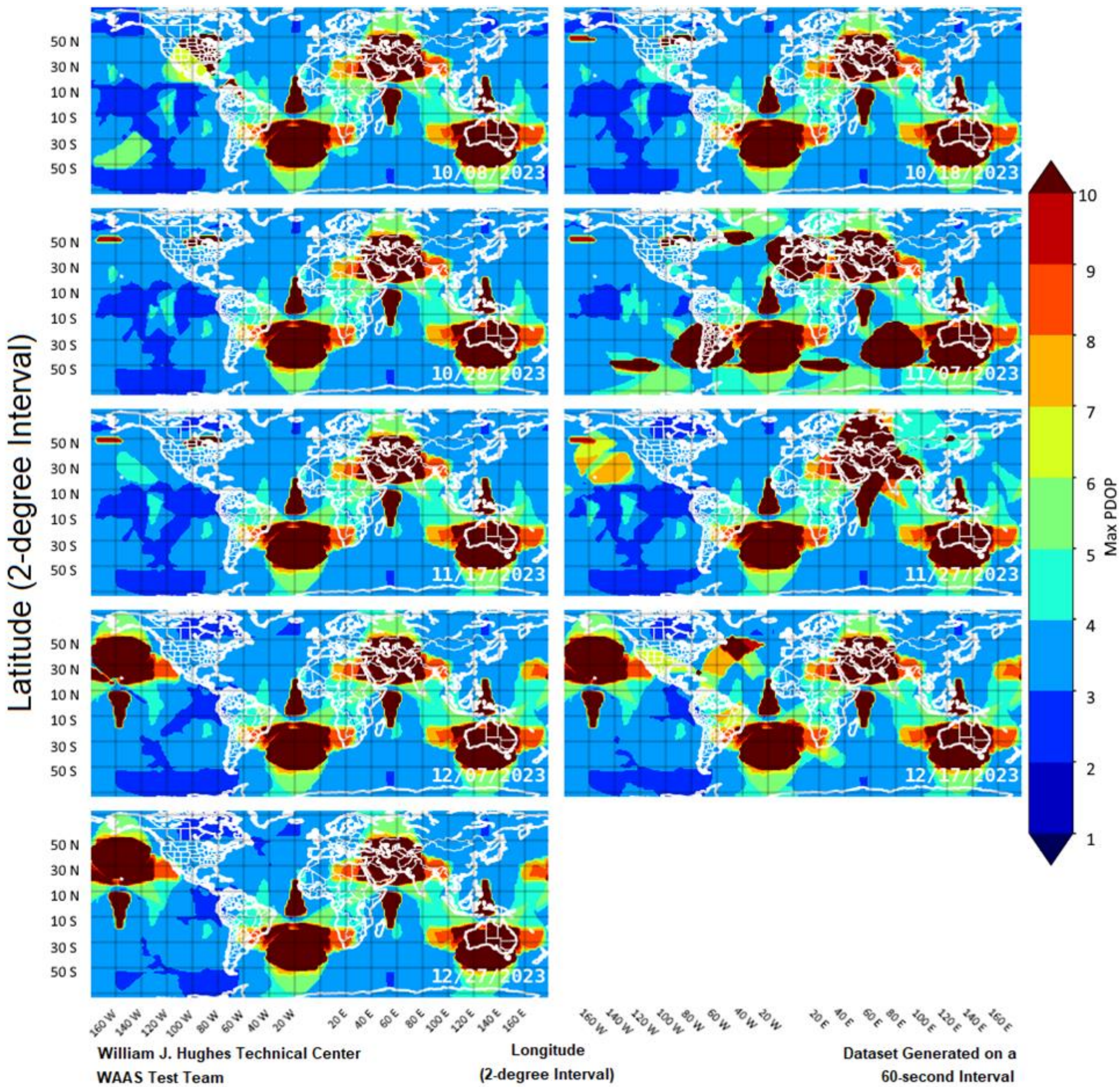

Figure B-0-8. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 8, 2023–December 27, 2023

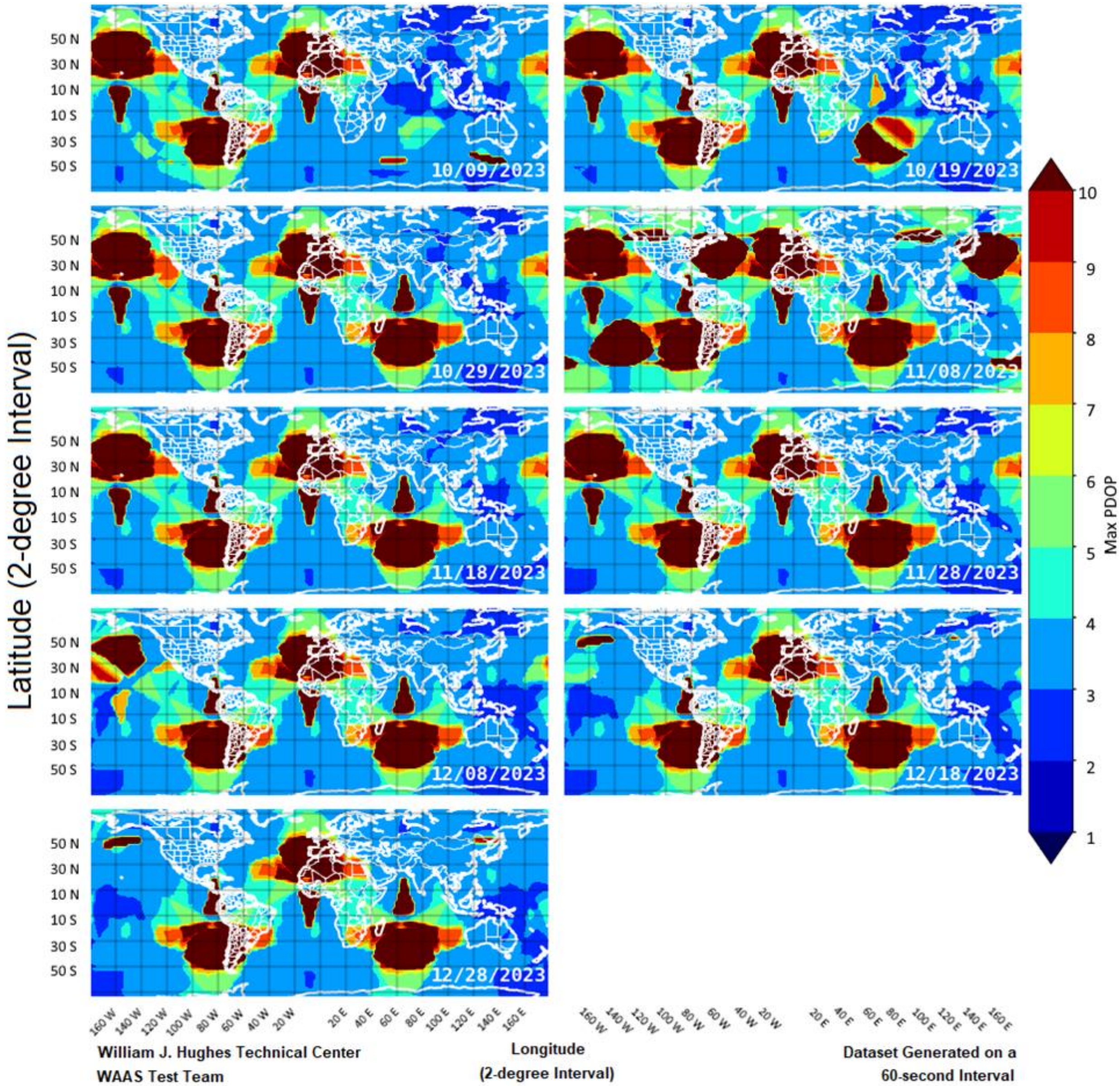

Figure B-0-9. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 9, 2023–December 27, 2023

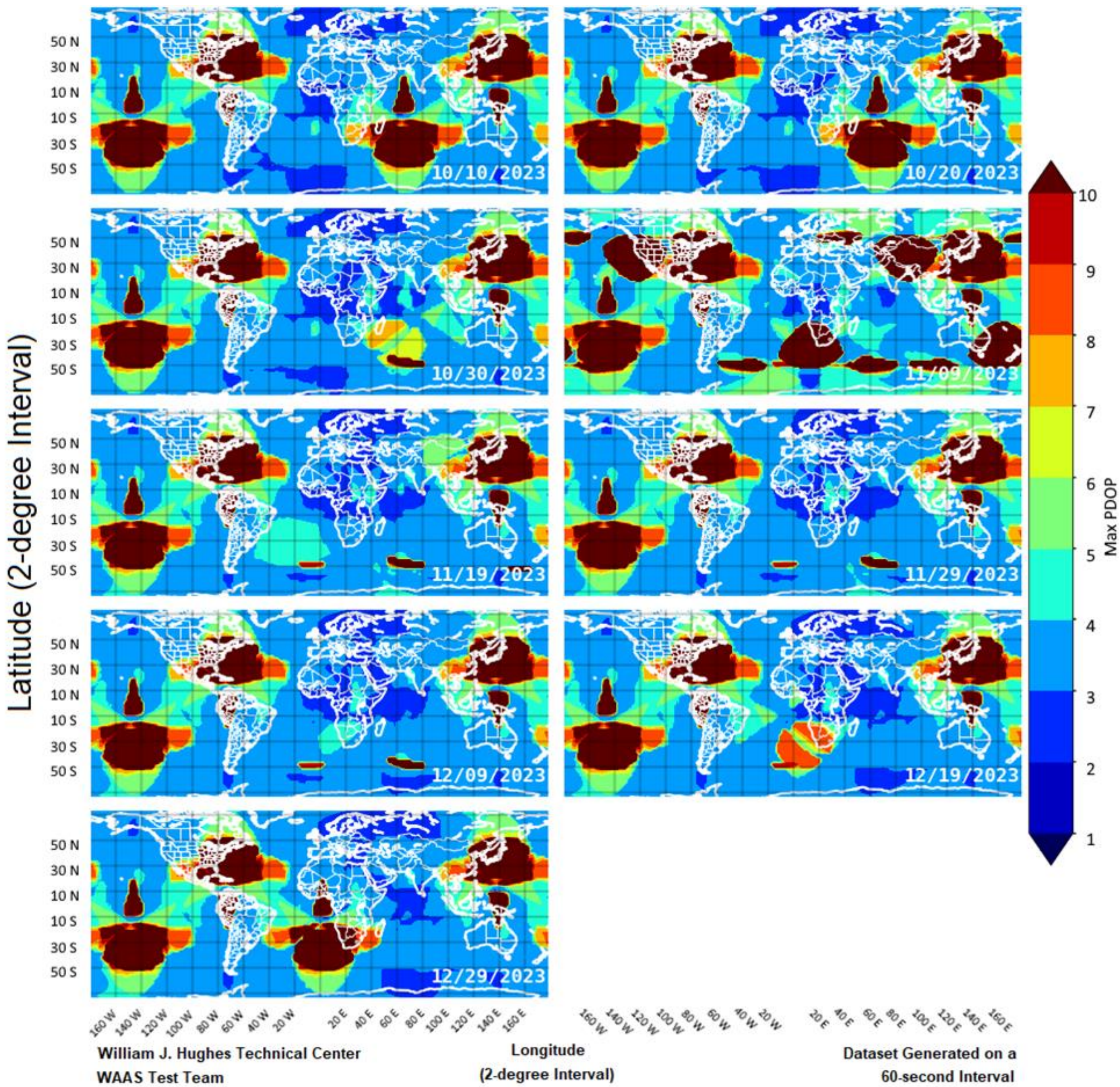

Figure B-0-10. Galileo Daily Maximum PDOP—Comparing 10-Day Geometry Cycle: October 10, 2023–December 29, 2023