

Revision 1, 05/12/2021: Updated Section 4 to describe how accuracy data will be handled in future reports.



Satellite Navigation Branch, ANG-E66

**GALILEO OPEN SERVICE
PERFORMANCE ANALYSIS REPORT**

April 2021

Report #1

Reporting Period: October 01 to December 31, 2020

<http://www.nstb.tc.faa.gov>

**FAA William J. Hughes Technical Center
Atlantic City International Airport, New Jersey 08405**

DOCUMENT VERSION CONTROL

VERSION	DESCRIPTION OF CHANGE	DATE
0.1	Initial Draft	03/04/2021
0.2	Tech Edit	03/10/2021
0.3	Section 6 Updated	03/11/2021
0.4	Group Tech Edit	03/15/2021
0.5	Peer Review	04/01/2021
0.6	External Peer Review	04/26/2021
1.0	Final Report	04/30/2021
2.0	Revision 1	05/12/2021

EXECUTIVE SUMMARY

In 2016, the European Union made available the Galileo global satellite navigation system [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 Global Navigation Satellite System similar to the United States' 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 1.1 [2]. The parameters included in this report or future reports are, with the high-level results for the quarter, are:

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 the almanacs posted on the European Global Navigation Satellite System Agency website and published Notices Advisory to Galileo Users (NAGUs), coverage data was calculated for each month in the reporting period. Availability of PDOP ranged from 99.18% to 99.99% for the months during this reporting period.

Signal Health and Accuracy F/NAV Signal-in-Space Accuracy (SISA). Using a Wide Area Augmentation System (WAAS) G-III receiver at the William J. Hughes Technical Center in Atlantic City, NJ, Galileo E5a F/NAV signals were tracked with the health assessed as per Figure 4 in the OS SDD v1.1 document [2]. During the Q4 2020, three marginal signal events were detected where the F/NAV E5a signal broadcasted a SISA index of 255, indicating no accuracy predication available (NAPA) from at least one satellite vehicle. The decoded F/NAV data from the NovAtel G-III receiver was examined along with any available NAGUs relevant to each event. Section 3.2 details data processing, cleansing, and modeling plans to assess signal-in-space ranging accuracy (SISRA) as per OS SDD v1.1, Section 3.3.2, Tables 9 and 10. This section will include SISRA 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 United States Naval Observatory (USNO) comparing Galileo system time as computed by its users, with that of the Universal Time Coordinated (UTC) standard of time produced by the USNO and other labs. The evaluation of both accuracy and availability of Galileo's time dissemination service will follow the descriptions in OS SDD v1.1, Sections 2.3.3 and 3.3.3, and 2.3.4 and 3.3.4, respectively.

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 v1.1, 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 v1.1, Section C.4.5.3.

This report does not include Galileo position accuracy obtained from receiver - satellite pseudorange measurements.

Timely Publication of NAGUS. The timeliness of NAGUs is based on the MPLs discussed in Section 3.6.1 of the Galileo OS SDD [2] using NAGUs published to the European GNSS Service Center website [3]. There was one planned NAGU published in a timely manner that affected service. There was one General NAGU not published in a timely manner that impacted service.

TABLE OF CONTENTS

1.	INTRODUCTION	1
2.	AVAILABILITY OF GALILEO POSITION DILUTION OF PRECISION.....	2
3.	SIGNAL HEALTH AND ACCURACY (F/NAV)	15
3.1	Healthy Signal Summary	15
3.1.1	Monthly F/NAV Signal Health Tracked at WJHTC.....	18
3.1.2	F/NAV Marginal Signal Health Events Tracked at WJHTC.....	20
3.2	Satellite Position Errors	23
3.2.1	SISRA	23
3.2.2	SISRA Quarterly Results	25
4.	GALILEO TIME TRANSFER PERFORMANCE	25
4.1	Availability	25
4.2	Accuracy	25
5.	GALILEO POSITIONING PERFORMANCE	26
5.1	Availability of the Galileo Positioning Service	26
5.2	Galileo Position Accuracy	26
6.	MPL OF THE TIMELY PUBLICATION OF NAGUS.....	27
7.	IGS DATA (POSITION ERRORS)	32
8.	ACRONYMS	33
9.	REFERENCES	35

LIST OF FIGURES

Figure 2-1. Availability of Galileo PDOP October 2020 (PDOP Availability Contour Color bar: 99.8%–100%)	4
Figure 2-2. Availability of Galileo PDOP November 2020 (PDOP Availability Contour Color bar: 99.0%–100%)	5
Figure 2-3. Availability of Galileo PDOP December 2020 (PDOP Availability Contour Color bar: 98.5%–100%)	6
Figure 2-4. World Galileo Maximum PDOP (October 30, 2020)	8
Figure 2-5. World Galileo Maximum PDOP (November 9, 2020)	10
Figure 2-6. World Galileo Maximum PDOP (November 10, 2020)	11
Figure 2-7. World Galileo Maximum PDOP (October 31, 2020)	12
Figure 2-8. World Galileo Maximum PDOP (November 11, 2020)	13
Figure 2-9. World Galileo Maximum PDOP (November 1, 2020)	14
Figure 3-1. Percentage of Time Healthy F/NAV Subframes Tracked from WJHTC	15
Figure 3-2. F/NAV Signal Health by SVID (Tracked at WJHTC October 2020).....	19
Figure 3-3. F/NAV Signal Health by SVID (Tracked at WJHTC November 2020).....	19
Figure 3-4. F/NAV Signal Health by SVID (Tracked at WJHTC December 2020)	20
Figure 3-5. Marginal F/NAV Signal (SVID 11 Tracked at WJHTC November 10–11).....	21
Figure 3-6. Marginal F/NAV Signal (SVID 1 Tracked at WJHTC December 7–9)	22
Figure 3-7. Marginal F/NAV Signal (Multiple SVIDs Tracked at WJHTC December 14).....	23
Figure 3-8. 200 User Locations	25

LIST OF TABLES

Table 2-1. Availability of PDOP Parameter	2
Table 2-2. Availability of PDOP	3
Table 3-1. Q4 2020 F/NAV E5a SVIDs by SISA	16
Table 3-2. Q4 2020 F/NAV E5a SISAs by SVID	17
Table 6-1. MPL of the Timely Publication of NAGUS.....	27
Table 6-2. NAGUs Affecting Satellite Availability	28
Table 6-3. NAGUs Forecasted to Affect Satellite Availability	28
Table 6-4. Galileo Satellite Maintenance Statistics	29
Table 6-5. Summary of Q4 Published NAGUs	30

1. INTRODUCTION

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

Galileo provides four services: Open Service (OS), Safety-of-Life Service, Commercial 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 Federal Aviation Administration (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's European Global Navigation Satellite Systems Agency (GSA) 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 Advanced Receiver Autonomous Integrity Monitoring (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 NovAtel G-III receiver located at the FAA William J. Hughes Technical Center (WJHTC) in Atlantic City, NJ collects 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 International GNSS Service (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 Service Definition Document (SDD), version 1.1 [2]. The parameters included in this report or future reports are:

- Signal-in-Space Ranging Accuracy (SISRA)
- Signal-in-Space (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 Notice Advisory to Galileo Users (NAGU)
- User Position Error (this parameter is not in the OS SDD; it will be evaluated in future reports)

The minimum performance levels (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 healthy during this quarter on November 30, 2020. This report does not include those two satellites in the performance assessment.

2. AVAILABILITY OF GALILEO POSITION DILUTION OF PRECISION

The availability of Galileo Position Dilution of Precision (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
$\geq 77\%$ 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 Team 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 almanacs were obtained from the European GSA [6]. Published almanacs were incorporated using the status of both E1b and E5a being healthy/marginal at the same time. Additionally, information provided in the NAGUs was incorporated to account for satellite maintenance and outages. Galileo auxiliary satellites, E14 and

E18, were not included in the calculations and data provided in this section. This report contains Galileo data processed from a NovAtel G-III receiver located at the FAA WJHTC. As we incorporate additional receiver data and increase the visibility of worldwide Galileo satellite ephemeris data, we plan to include the capability of using ephemeris data in DOP processing. DOPs were calculated at every 2-degree grid between longitudes 180W to 180E and latitudes 74S to 74N at 1-minute intervals. This resulted in 1440 samples for each of the 13,500 grid points over a 24-hour period. 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: $\geq 77\%$)
October 2020	99.99803%
November 2020	99.93169%
December 2020	99.18253%

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 areas' 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 vary for each plot. The Availability of PDOP for December (Figure 2-3) was not 100% at any grid point due to the December 14, 2020 NAGU (2020021) that is discussed in this section and in Section 6.

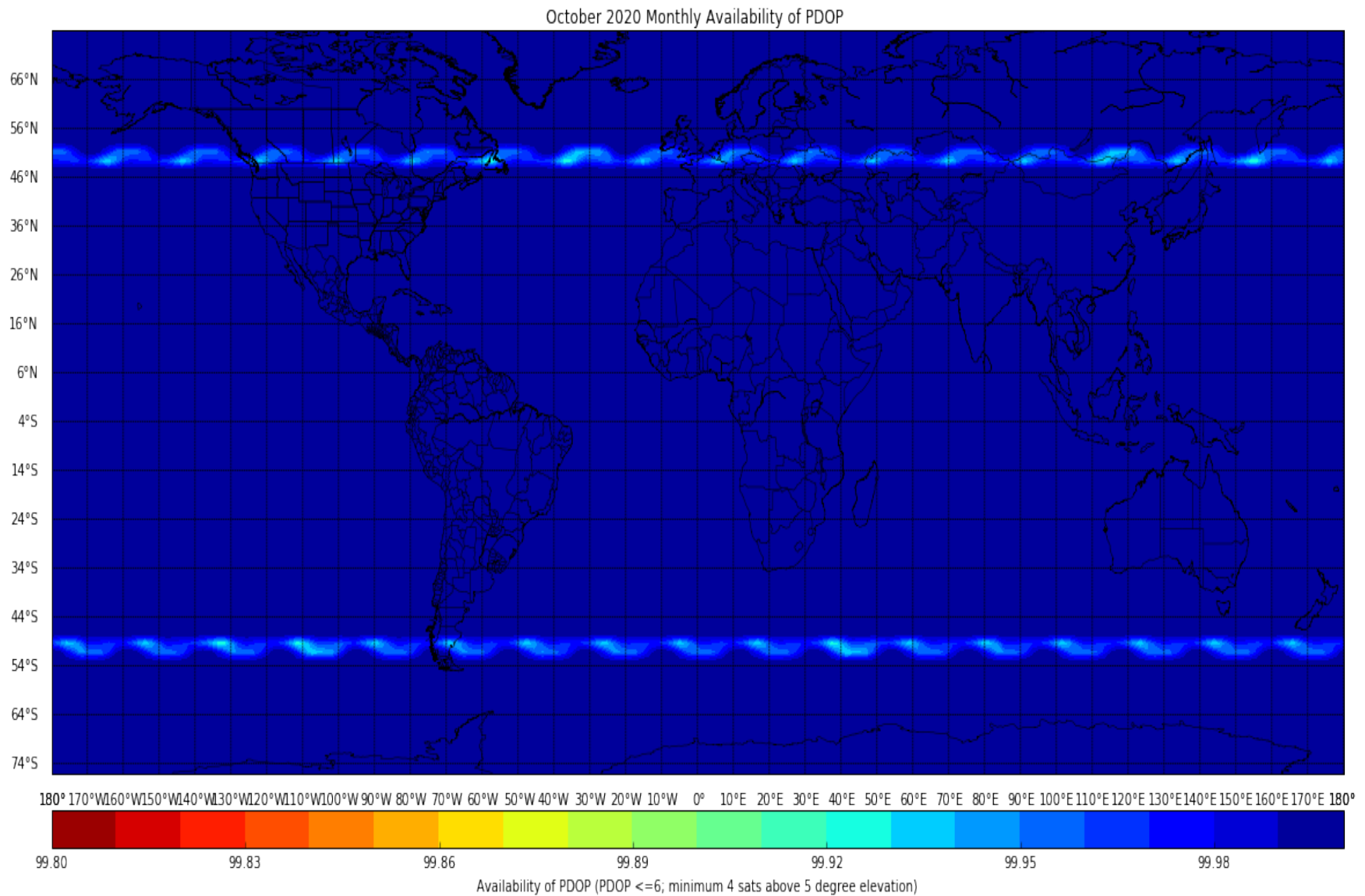


Figure 2-1. Availability of Galileo PDOP October 2020 (PDOP Availability Contour Color bar: 99.8%–100%)

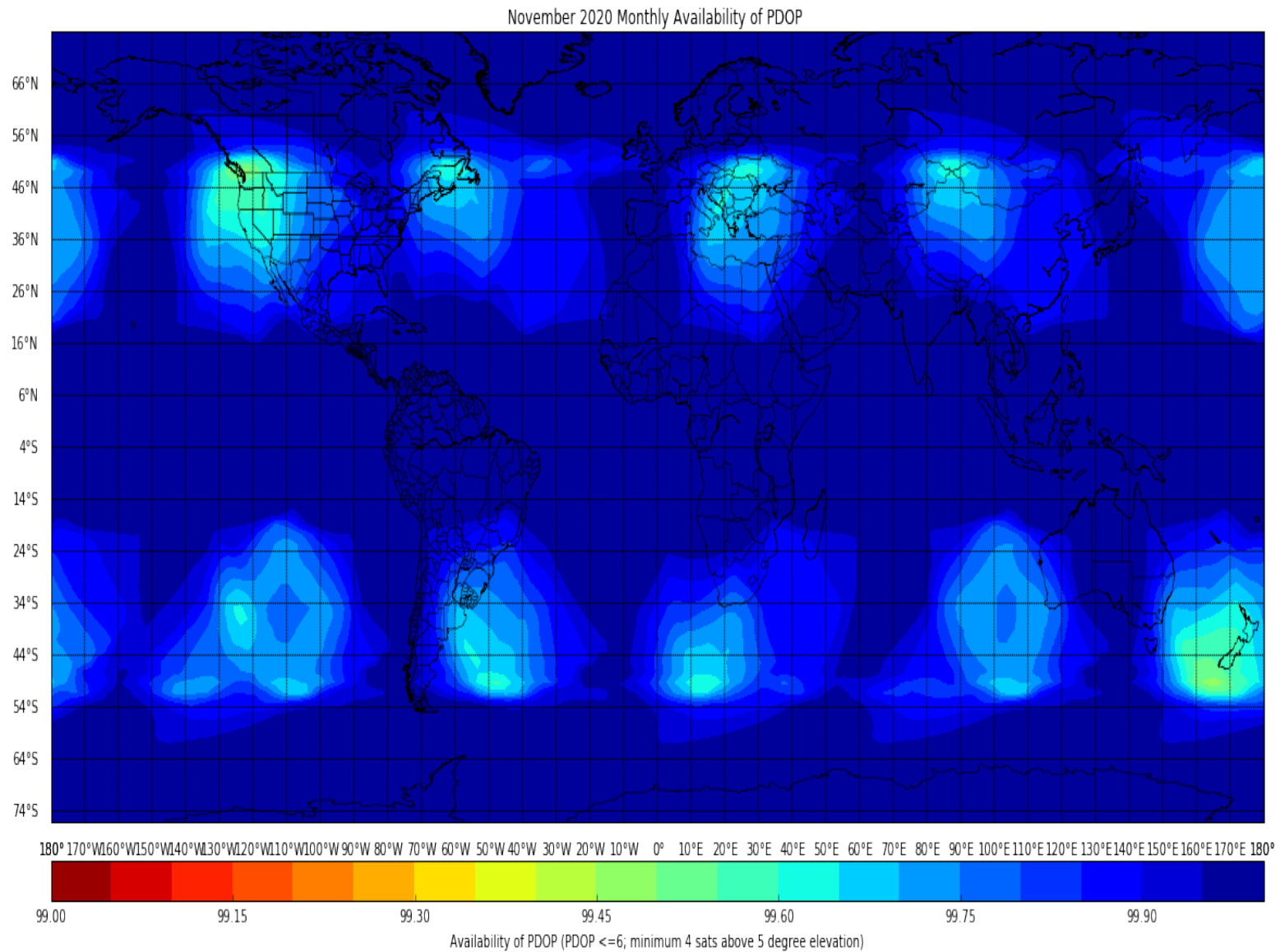


Figure 2-2. Availability of Galileo PDOP November 2020 (PDOP Availability Contour Color bar: 99.0%–100%)

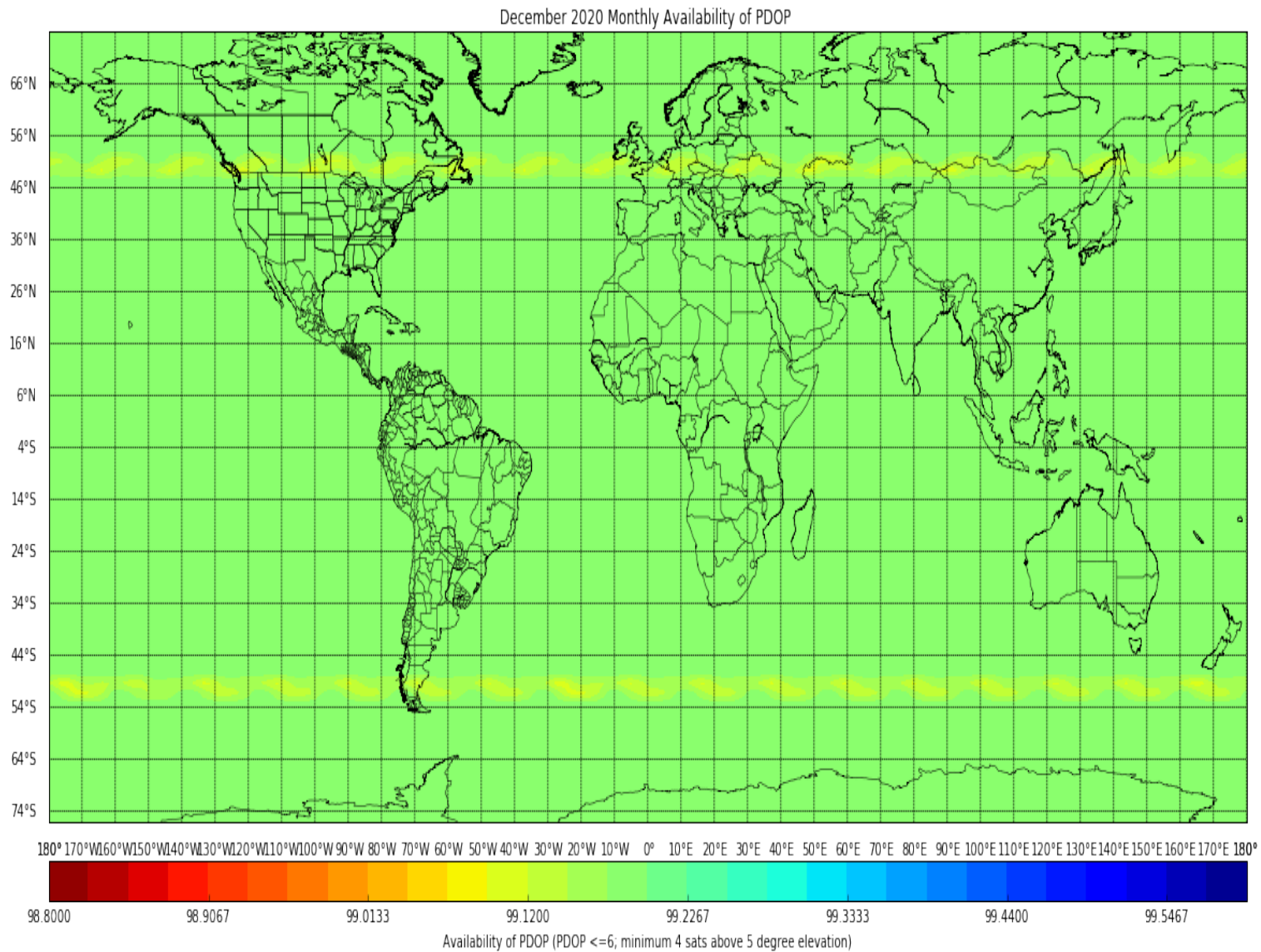


Figure 2-3. Availability of Galileo PDOP December 2020 (PDOP Availability Contour Color bar: 98.5%–100%)

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 shows typical PDOP performance during the quarter, 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.

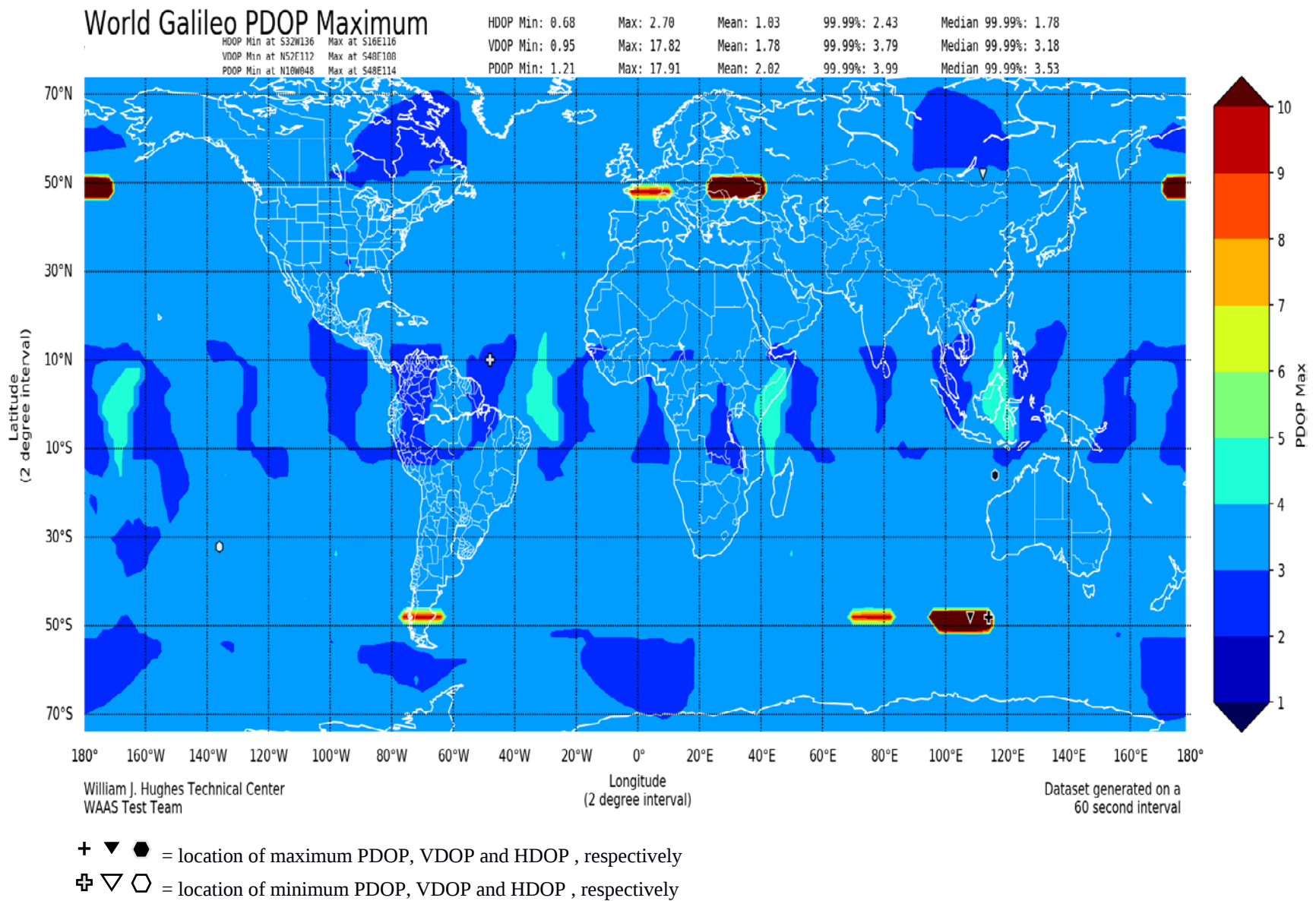


Figure 2-4. World Galileo Maximum PDOP (October 30, 2020)

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 2 events that affected Galileo PDOP. SVID 11 was unusable from 06:18 GMT on November 9, 2020 to 08:20 GMT on November 11, 2020 (NAGU 2020018). Figure 2-5 shows the maximum PDOP contour plot for November 9, 2020. Figure 2-4 can be referenced to show the maximum PDOP plot on October 30, 2020 (10 days earlier) with similar Galileo constellation and no NAGU events. Figure 2-6 shows the maximum PDOP plot for November 10, 2020 (NAGU 2020018), and Figure 2-7 shows the maximum PDOP plot on October 31, 2020 with no events. Figure 2-8 shows the maximum PDOP plot for November 11, 2020 (NAGU 2020018), and Figure 2-9 shows the maximum PDOP plot on November 1, 2020 with no events. On December 14, 2020, a general NAGU (2020021) was issued reporting service degradation on all Galileo satellites. Signals did not meet the MPLs defined in the OS SDD from 00:00 GMT to 06:12 GMT. All Galileo satellites were set to marginal during this time. Section 3.1 details the satellite health during these time periods, and Section 6 provides NAGU information.

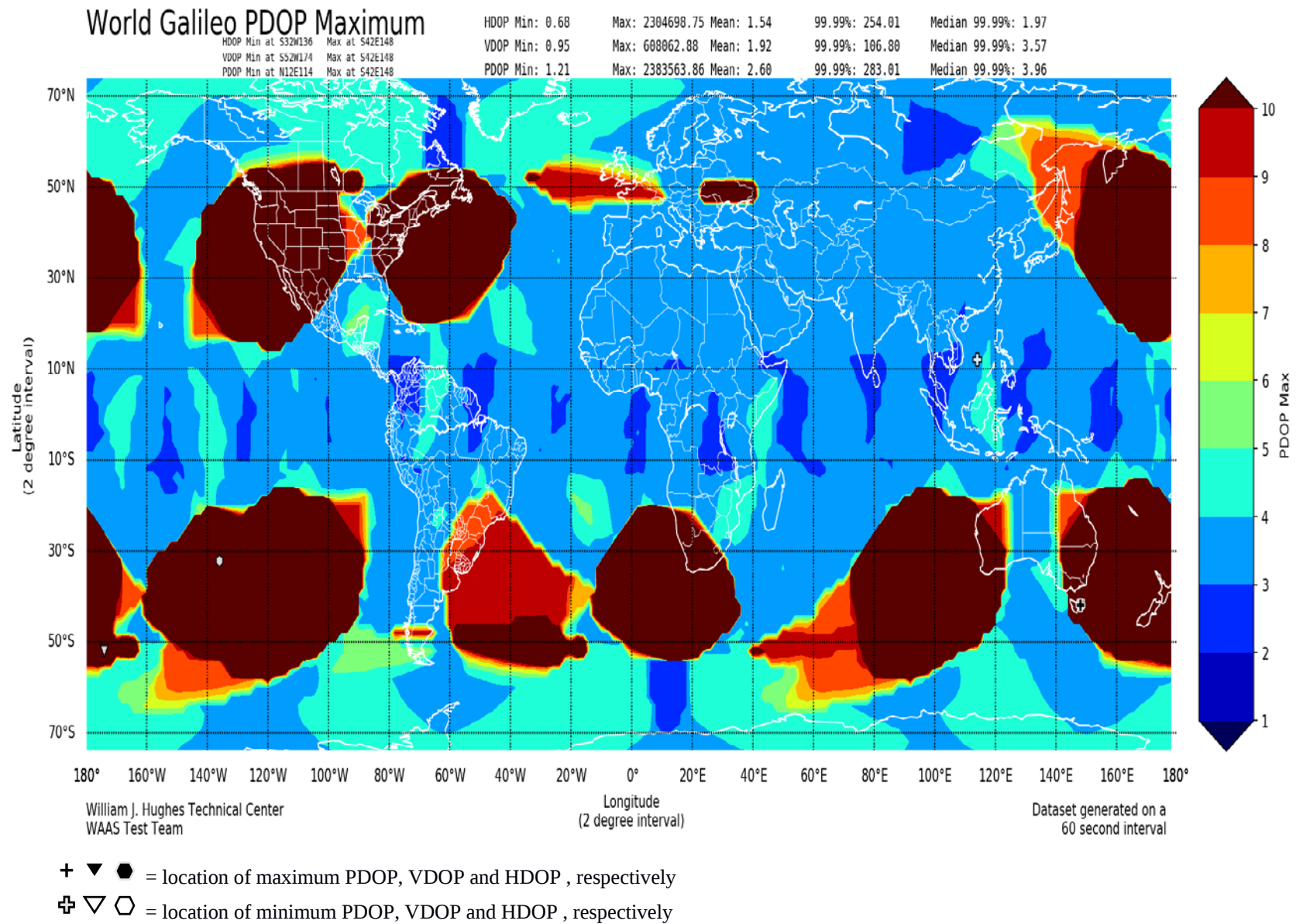


Figure 2-5. World Galileo Maximum PDOP (November 9, 2020)

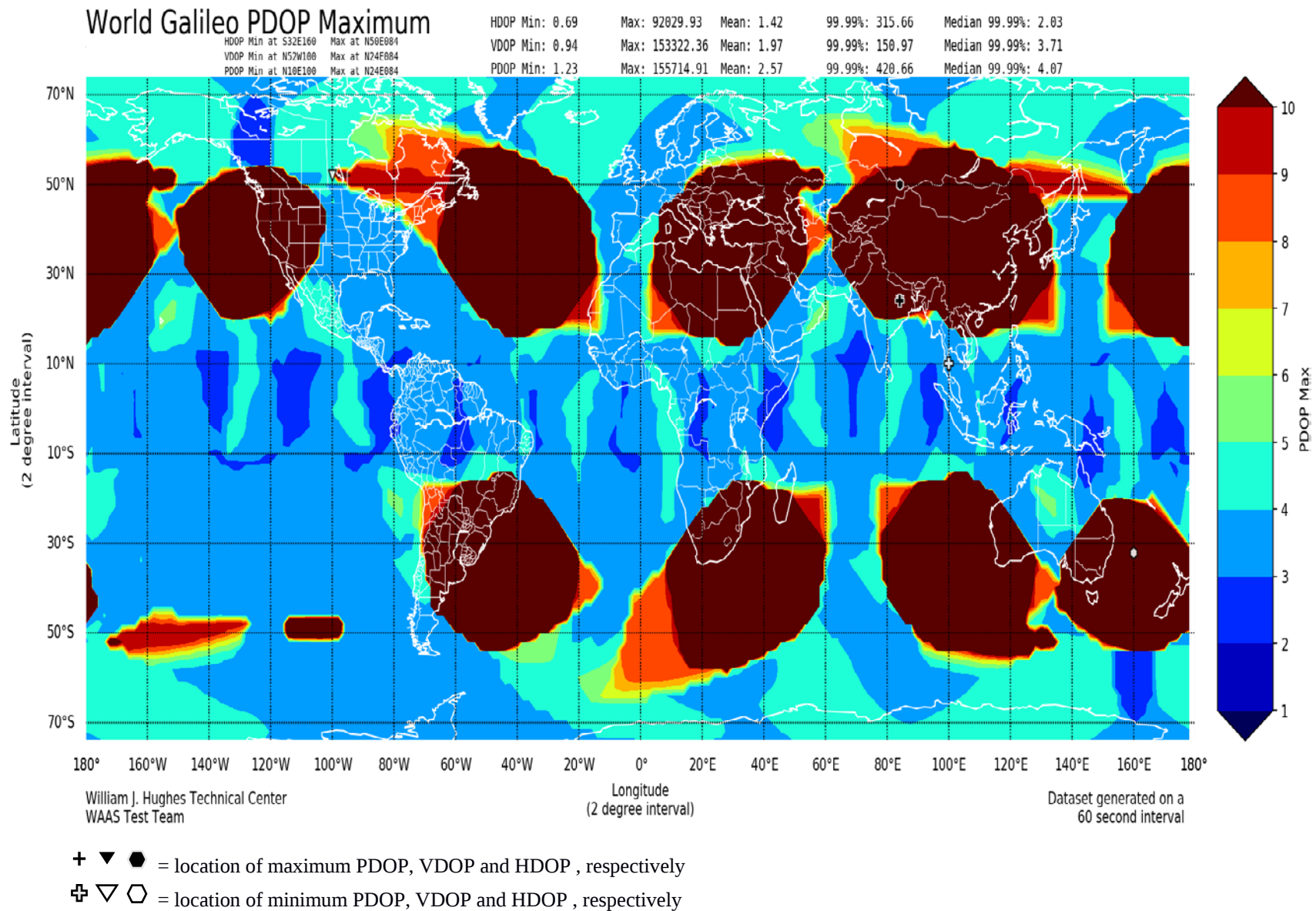


Figure 2-6. World Galileo Maximum PDOP (November 10, 2020)

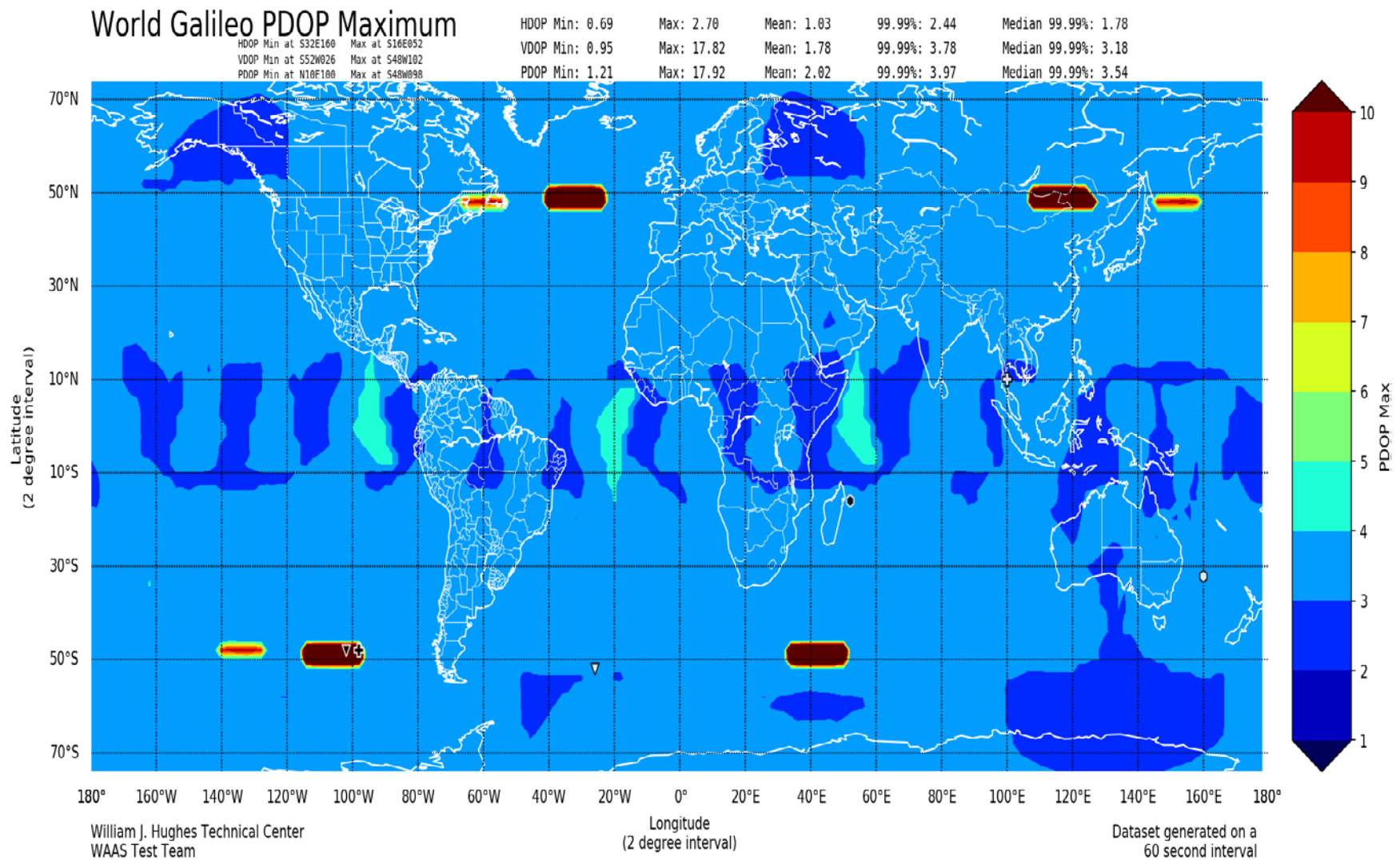


Figure 2-7. World Galileo Maximum PDOP (October 31, 2020)

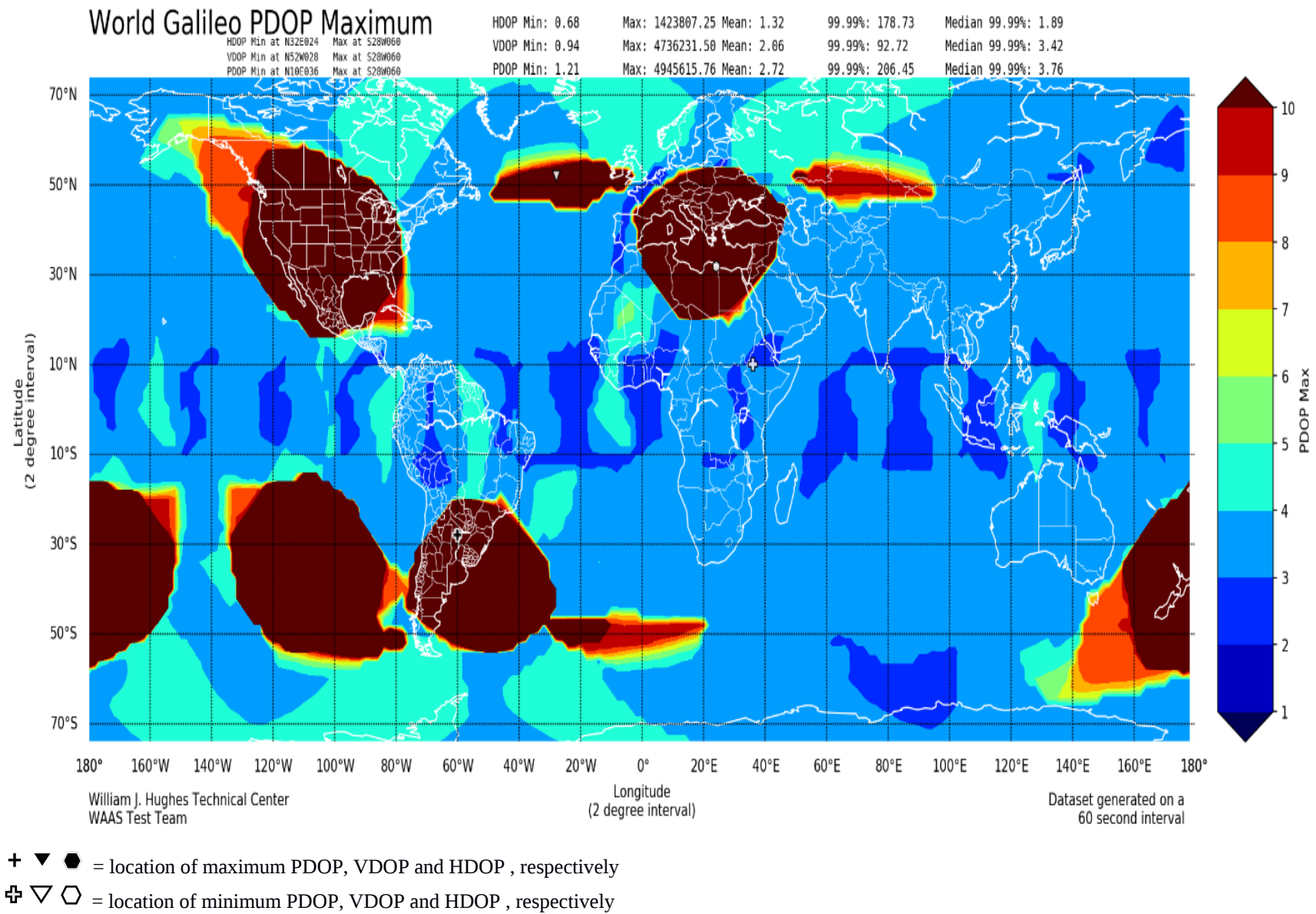


Figure 2-8. World Galileo Maximum PDOP (November 11, 2020)

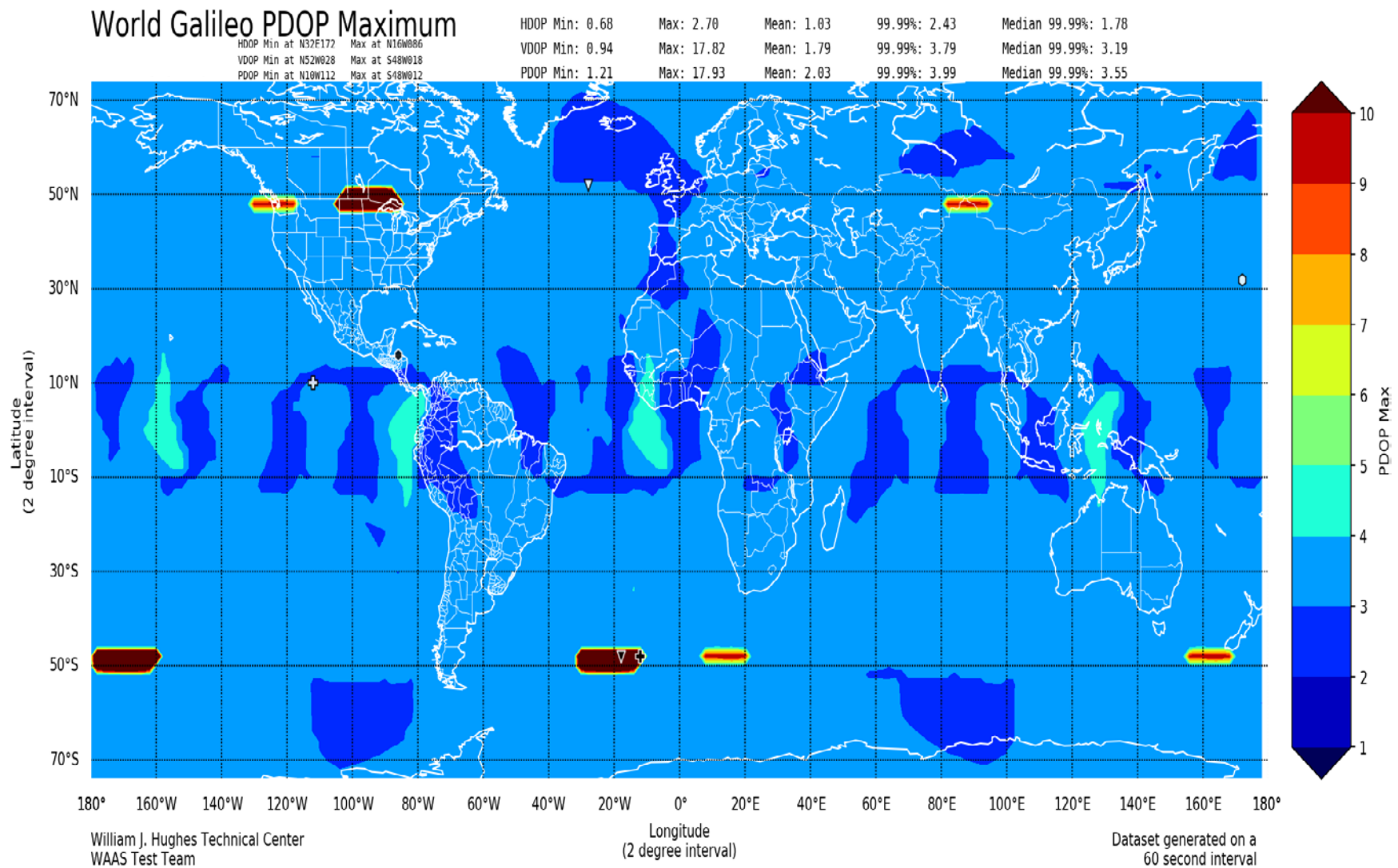


Figure 2-9. World Galileo Maximum PDOP (November 1, 2020)

3. SIGNAL HEALTH AND ACCURACY (F/NAV)

3.1 Healthy Signal Summary

The Galileo OS SDD v1.1, Section 2.3.1.4 discusses the mapping of SIS status flags with the SIS status. Figure 3-1 shows the percentage of time that the E5a signal received at WJHTC with a Wide Area Augmentation System (WAAS) G-III receiver demodulated F/NAV data from the E5a signal which would be interpreted as a healthy signal following the decision tree described in Figure 4 of the OS SDD v1.1. 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. Excluding auxiliary satellites E14 and E18, 1,201,720 F/NAV subframes across 22 SVIDs were evaluated during the Q4 2020 period.

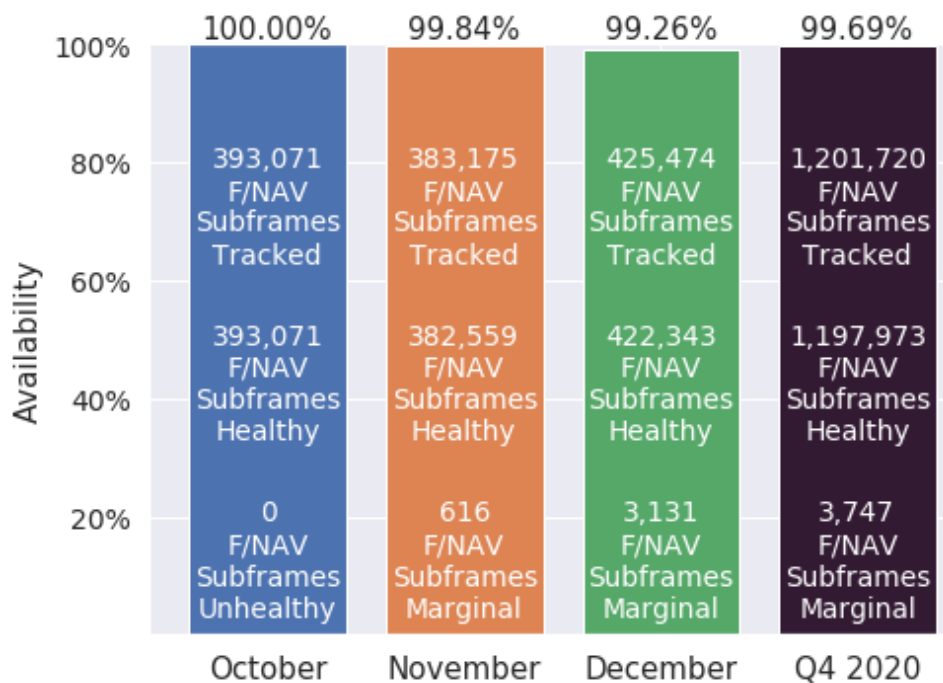


Figure 3-1. Percentage of Time Healthy F/NAV Subframes Tracked from WJHTC

Table 3-1 provides a count of each individual F/NAV subframe received with the NovAtel G-III receiver at WJHTC, grouping the counts by the signal-in-space accuracy (SISA) index first then by the SVID. Table 3-2 provides the same counts where the grouping instead begins with the SVID followed by the SISA index.

Table 3-1. Q4 2020 F/NAV E5a SVIDs by SISA

SISA	SVID	# of Subframes	Signal Health Status (SHS)	Data Validity Status (DVS)
107	1	56697	0	0
	2	58078	0	0
	3	58155	0	0
	4	57204	0	0
	5	58329	0	0
	7	56837	0	0
	8	56972	0	0
	9	57581	0	0
	11	55779	0	0
	12	56999	0	0
	13	58379	0	0
	15	58503	0	0
	19	55983	0	0
	21	57117	0	0
	24	57879	0	0
	25	57829	0	0
	26	57682	0	0
	27	57731	0	0
	30	58155	0	0
	31	57741	0	0
	33	22873	0	0
	36	23167	0	0
108	1	258	0	0
	3	149	0	0
	7	230	0	0
	8	271	0	0
	12	51	0	0
	13	243	0	0
	15	84	0	0
	19	8	0	0
	21	260	0	0
	24	76	0	0
	26	288	0	0
	27	53	0	0
	31	254	0	0
110	11	78	0	0

SISA	SVID	# of Subframes	SHS	DVS
255	1	920	0	0
	2	308	0	0
	3	132	0	0
	5	129	0	0
	8	195	0	0
	9	28	0	0
	11	892	0	0
	12	276	0	0
	24	237	0	0
	25	206	0	0
	30	38	0	0
	31	130	0	0
	33	42	0	0
	36	214	0	0

Table 3-2. Q4 2020 F/NAV E5a SISAs by SVID

SVID	SISA	# of Subframes
1	107	56697
	108	258
	255	920
2	107	58078
	255	308
3	107	58155
	108	149
	255	132
4	107	57204
5	107	58329
	255	129
7	107	56837
	108	230
8	107	56972
	108	271
	255	195
9	107	57581
	255	28
11	107	55779
	110	78
	255	892

SVID	SISA	# of Subframes
12	107	56999
	108	51
	255	276
13	107	58379
	108	243
15	107	58503
	108	84
19	107	55983
	108	8
21	107	57117
	108	260
24	107	57879
	108	76
	255	237
25	107	57829
	255	206
26	107	57682
	108	288
27	107	57731
	108	53
30	107	58155
	255	38
31	107	57741
	108	254
	255	130
33	107	22873
	255	42
36	107	23167
	255	214

3.1.1 Monthly F/NAV Signal Health Tracked at WJHTC

Figure 3-2 through 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. A firmware upgrade to the NovAtel G-III receiver applied in November 2021 resolved an issue tracking SVID 33 and SVID 36. Healthy F/NAV subframes are marked in green and marginal subframes are marked red.

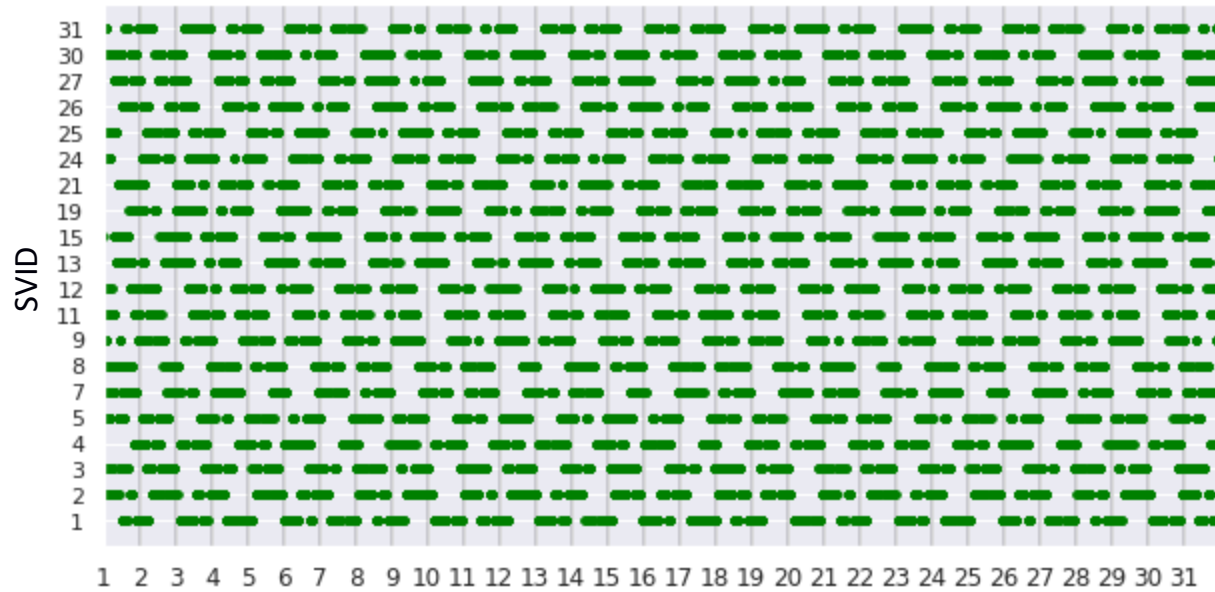


Figure 3-2. F/NAV Signal Health by SVID (Tracked at WJHTC October 2020)

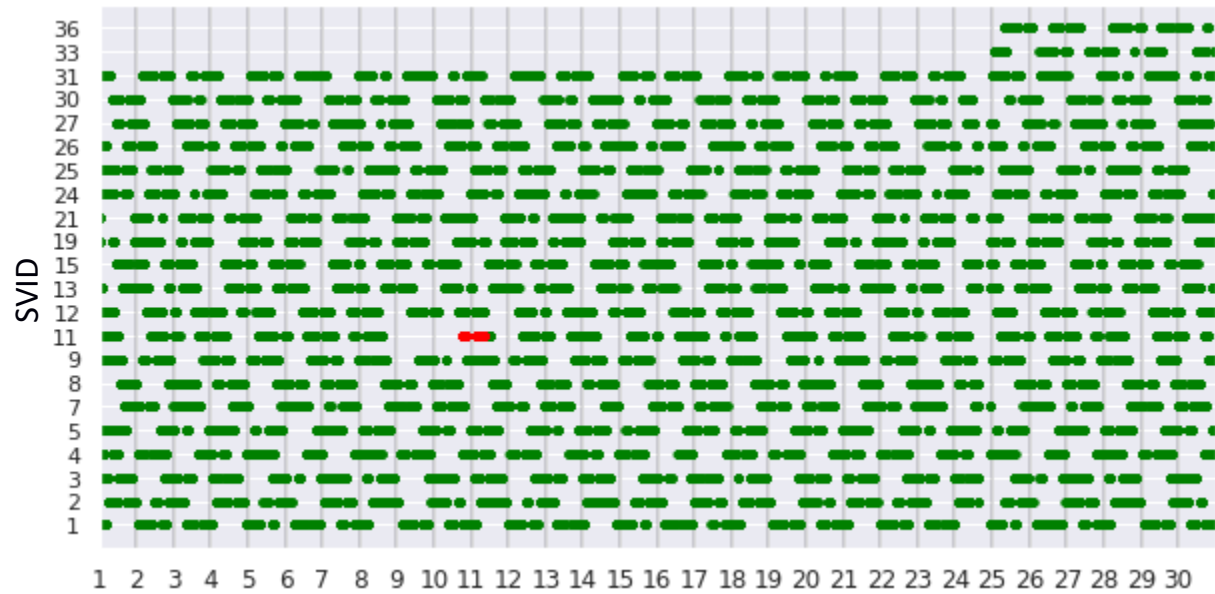


Figure 3-3. F/NAV Signal Health by SVID (Tracked at WJHTC November 2020)

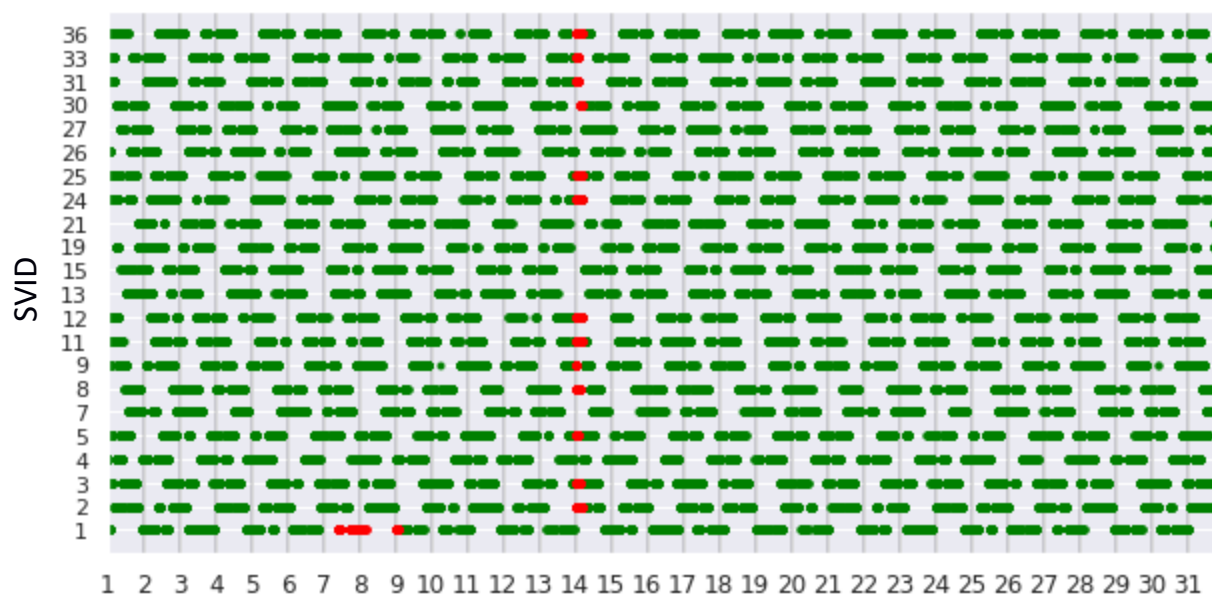


Figure 3-4. F/NAV Signal Health by SVID (Tracked at WJHTC December 2020)

3.1.2 F/NAV Marginal Signal Health Events Tracked at WJHTC

The following sections examine in closer detail the F/NAV Page 1 SISA index and F/NAV Pages 1–3 IOD_{nav} from during the 3 periods in Q4 2020 when marginal F/NAV signals were detected with a NovAtel G-III receiver at WJHTC in Atlantic City.

3.1.2.1 SVID 11 November 10–11, 2020

The times when the F/NAV signal on SVID 11 was tracked in a marginal state due to the SISA index indicating No Accuracy Prediction Available (NAPA) state were covered by the forecasted NAGU 2020017 (see Figure 3-5). The signal returned to a healthy state slightly before the usable time published in NAGU 2020018.

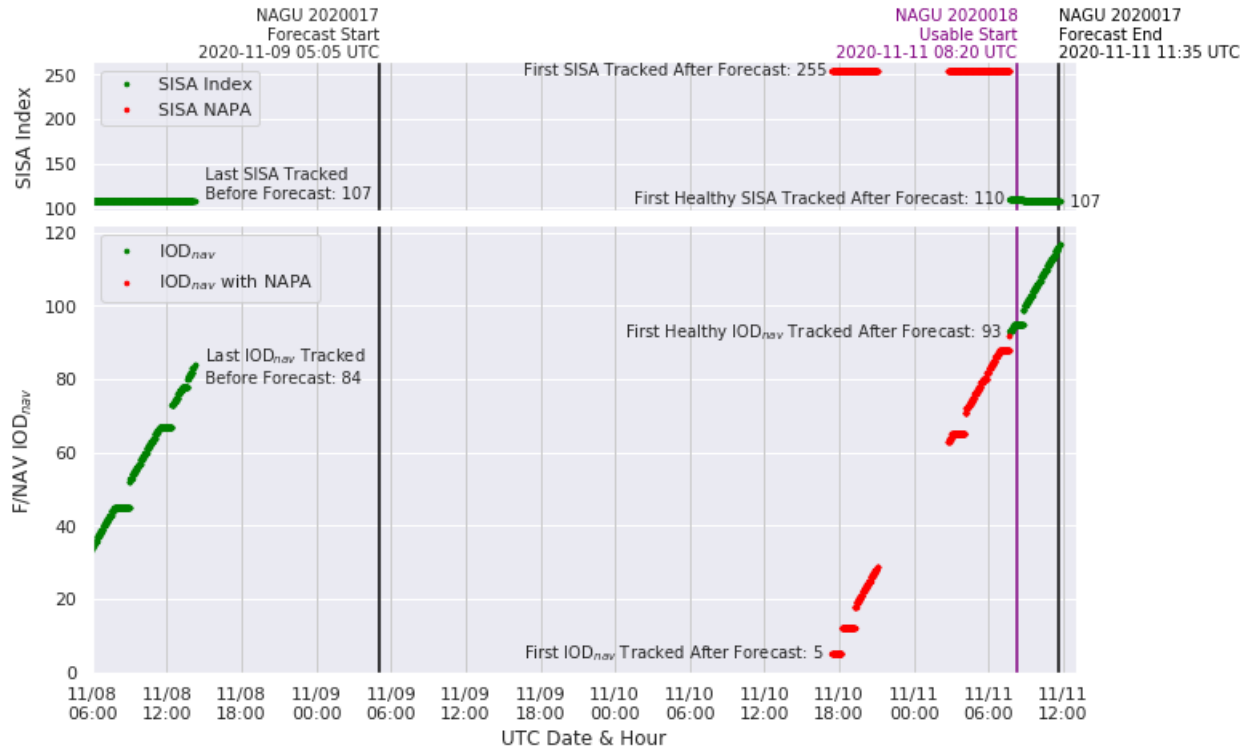


Figure 3-5. Marginal F/NAV Signal (SVID 11 Tracked at WJHTC November 10–11)

3.1.2.2 SVID 1 December 7–8, 2020

On December 7 at 09:13:10 Universal Time Coordinated (UTC), the NovAtel G-III receiver at WJHTC tracked the F/NAV signal on SVID 1 broadcasting a SISA index of 255 (see Figure 3-6). The last seen F/NAV subframe in NAPA state was framed on December 9 at 01:41:30 UTC. No associated NAGU appears to refer to this event on the SVID 1 F/NAV signal. An inquiry to the Galileo Service Center, ticket #1057, provided the following explanation as to why a NAGU was not issued:

“The Signal In Space Accuracy (SISA) is a prediction of the minimum standard deviation of the unbiased Gaussian distribution which overbounds the Signal In Space Error (SISE) predictable distribution for all possible user locations within the satellite coverage area. When no accurate prediction is available (SISA=NAPA), this is an indicator of a potential anomalous SIS. As consequence, the SIS Status was Marginal. In this case, the users were protected with the status of the broadcast SIS. It was not an outage in the satellite service, and for this reason, no NAGU was raised.”

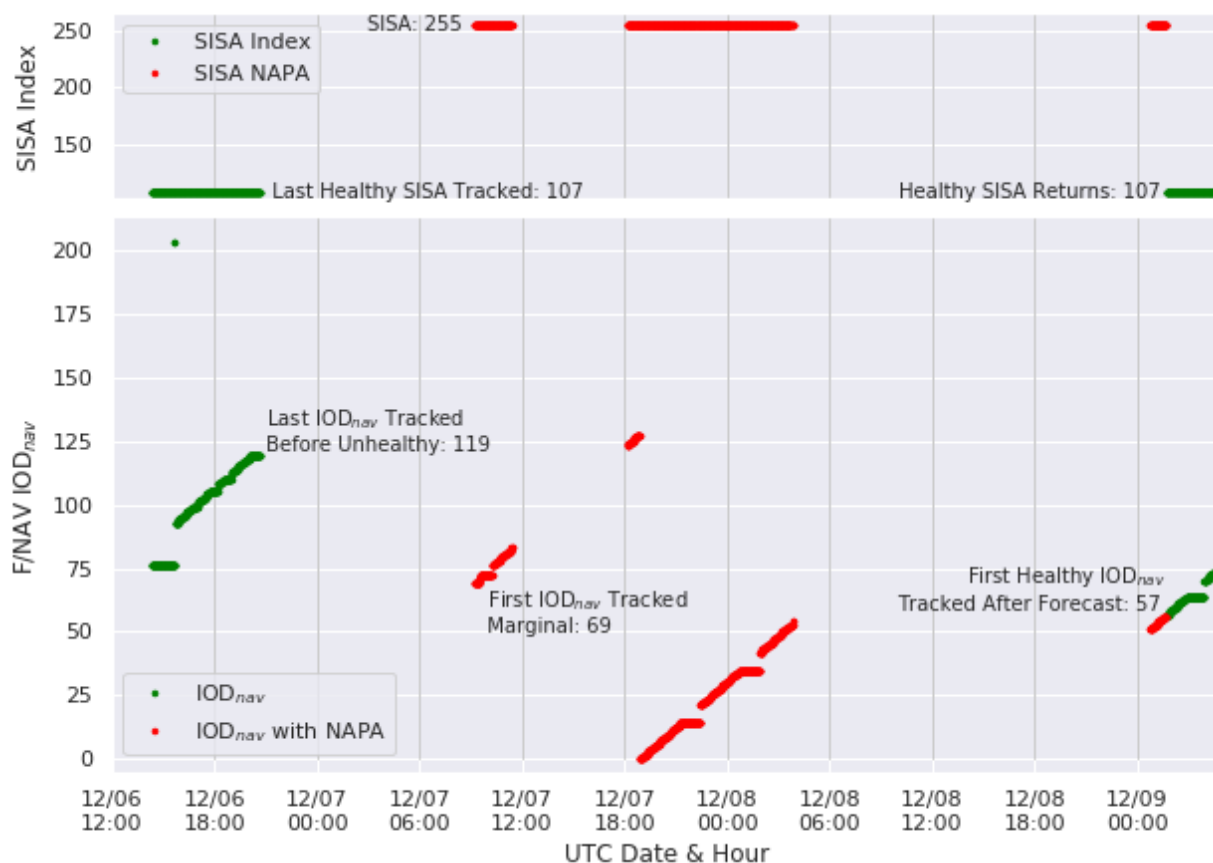


Figure 3-6. Marginal F/NAV Signal (SVID 1 Tracked at WJHTC December 7–9)

3.1.2.3 Multiple SVIDs December 14, 2020

On December 14 at 00:02:20 UTC, the NovAtel G-III receiver at WJHTC tracked the F/NAV signal on SVIDs 5, 9, 11, 12, and 31 broadcasting a SISA index of 255. The broadcast of NAPA state on the F/NAV signal continued for approximately 4 hours, with SVID 2 sending the last NAPA state at 04:44:50 UTC. Figure 3-7 provides the first and last UTC timestamps with a SISA index of 255 for each SVID.

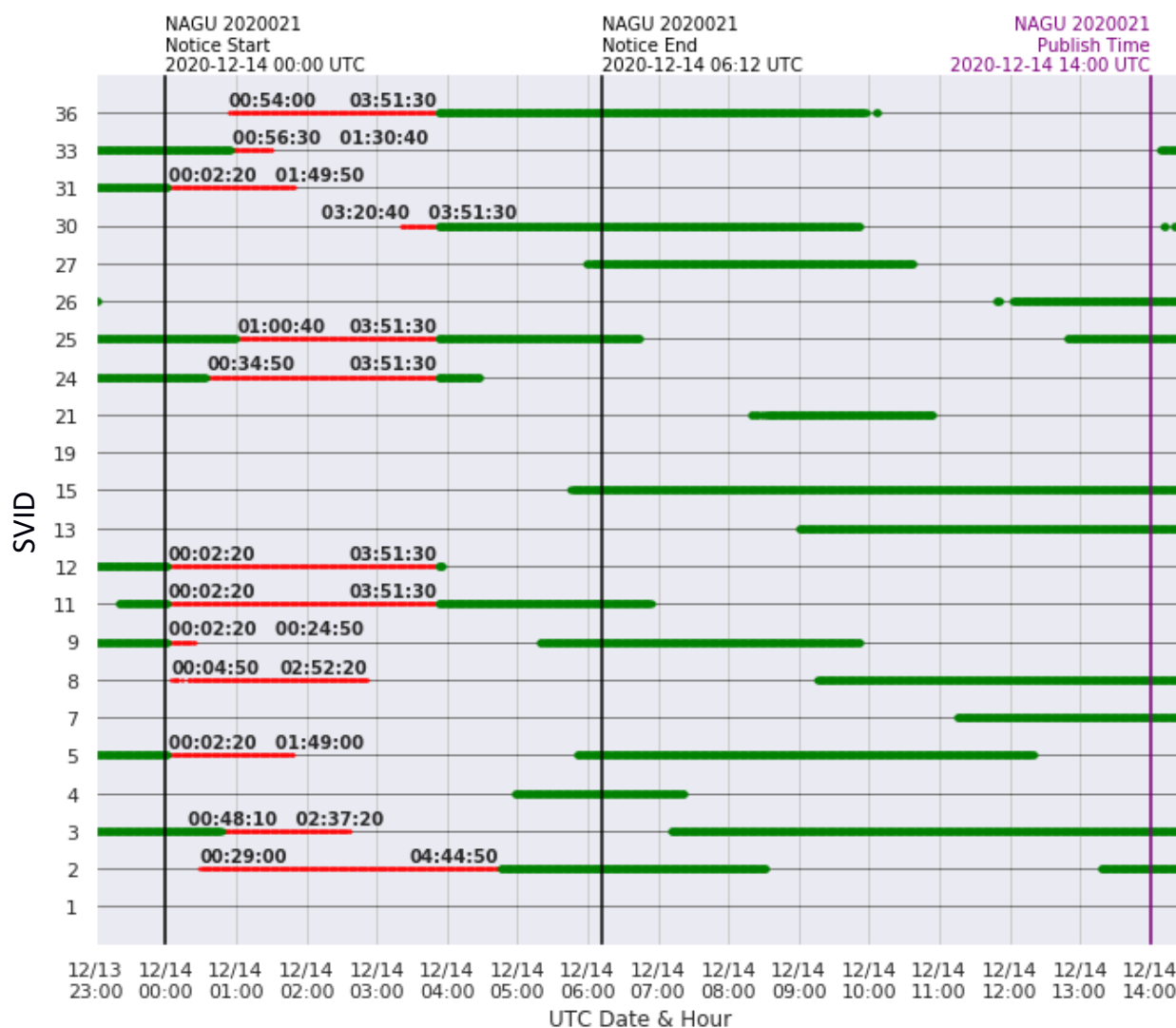


Figure 3-7. Marginal F/NAV Signal (Multiple SVIDs Tracked at WJHTC December 14)

3.2 Satellite Position Errors

3.2.1 SISRA

This section is planned for future reports. It will present the SISRA for each individual satellite as well as the SISRA over all satellites to evaluate the MPLs as described in OS SDD v1.1, Section 3.3.2, 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 [7]. 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 [8] [9].

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 is downloaded from the Crustal Dynamics Data Information System (CDDIS) [10] archive site. Precise Multi-GNSS Experiment (MGEX) data is 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 [11].

3.2.1.3 Error Computation

For each time step when precise data is available, all valid broadcast navigation data over all age of data (AOD) is 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 also projected onto Earth 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.

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 [12]. MPE is computed for each satellite, at each epoch. UPE is 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 3-9 shows the

200 user locations. The UPE at these points and the MPE are used to evaluate the SISRA as described in OS SDD v1.1, Section 3.3.2, Tables 9 and 10.

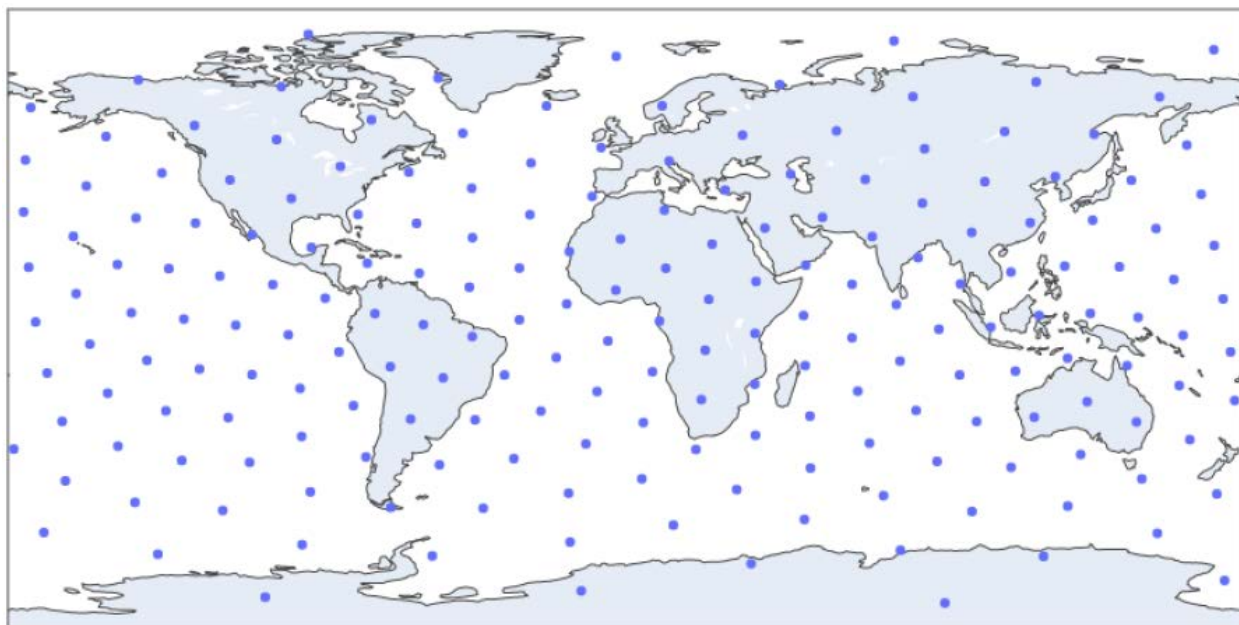


Figure 3-8. 200 User Locations

3.2.2 SISRA Quarterly Results

Figures in this section will present the SISRA for each individual satellite as well as the SISRA 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 will be provided by the United States Naval Observatory (USNO) website [13]. 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. Data will be presented in future reports.

5.1 Availability of the Galileo Positioning Service

Figures in this section will 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 v1.1, Section 3.4.4, Table 16 and 17. Sections 3.2.1–3.2.3 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 v1.1, Section C.4.5.3.

5.2 Galileo Position Accuracy

Galileo user position errors are not constrained by MPLs according to the Galileo OS SDD. The data that pertains to this section is assessed as 30-day 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 a FAA WJHTC Satellite Navigation (ANG-E66) NovAtel G-III receiver 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 Team is currently working to incorporate and validate other test receivers processing Galileo navigation and measurement data into this report.

NovAtel G-III firmware upgrades were installed on the WJHTC receiver to track and process the Galileo constellation satellite measurements. Current analysis of receiver performance,

environment, and firmware is ongoing; therefore, user position data is not available for the time period of this report. Future reports will include histograms of the calculated horizontal position error (HPE) and vertical position error (VPE) over a 1-month period, highlighting the 95th percentile. As more receivers are incorporated in the Galileo user solution processing, the histograms will provide an overall HPE and VPE, respectively.

6. MPL OF THE TIMELY PUBLICATION OF NAGUS

The Galileo OS SDD v1.1, 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 24 hours before the event occurs, and 2) if a NAGU is categorized as unplanned, it must be published within 72 hours of the event that occurred (see Table 6-1).

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 • ≥ 24 hours before the service is affected	• Including both Planned and General NAGUs
For unscheduled outages or events affecting the service • ≤ 72 hours after the event affecting the service is detected	• Only for Unplanned NAGUs

Satellite availability performance was analyzed based on published NAGUs. During this reporting period, October 1 through December 31, 2020, there were 2 reported outages. One outage was a planned activity and was reported in advance, and one was a General NAGU which was reported after the outage occurred. A complete listing of outage NAGUs for the reporting period is provided in Table 6-5.

Table 6-2 provides a summary of the time each NAGU affected 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 Availability

NAGU	SVID	Type	Start	End	Total Unscheduled	Total Scheduled	Total
2020018	11	USABLE	09 Nov 2020 06:18 UTC	11 NOV 2020 08:20 UTC	0	50.03	50.03
2020021	1	GENERAL (NOTICE)	14 Dec 2020 00:00 UTC	14 Dec 2020 06:12 UTC	6.03	0	6.03
	2				6.03	0	6.03
	3				6.03	0	6.03
	4				6.03	0	6.03
	5				6.03	0	6.03
	7				6.03	0	6.03
	8				6.03	0	6.03
	9				6.03	0	6.03
	11				6.03	0	6.03
	12				6.03	0	6.03
	13				6.03	0	6.03
	15				6.03	0	6.03
	19				6.03	0	6.03
	21				6.03	0	6.03
	24				6.03	0	6.03
	25				6.03	0	6.03
	26				6.03	0	6.03
	27				6.03	0	6.03
	29				6.03	0	6.03
	31				6.03	0	6.03
	33				6.03	0	6.03
	36				6.03	0	6.03
Totals of Unscheduled Scheduled and Total Downtime					132.66	50.03	182.69

Table 6-3 provides a summary of NAGUs published which forecast satellite outages.

Table 6-3. NAGUs Forecasted to Affect Satellite Availability

NAGU	SVID	TYPE	Start	End	Total	Comments
2020017	11	PLN_OUTAGE	09 Nov 2020	11 Nov 2020	54.50	2020018

			05:05 UTC	11:35 UTC		
Total Forecasted Downtime					54.50	

Table 6-4 provides a summary of Satellite Reliability, Maintainability, and Availability data. This data is being 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 6-4. Galileo Satellite Maintenance Statistics

Satellite Availability Parameter	
Total Forecasted Downtime (hrs)	54.50
Total Actual Downtime (hrs)	182.69
Total Actual Scheduled Downtime (hrs)	50.03
Total Actual unscheduled Downtime (hrs)	132.66
Total Satellite Outages	23
Scheduled Satellite Outages	1
Unscheduled Satellite Outages	22
Percent Operational – Scheduled Downtime (%)	99.91
Percent Operational – All Downtime (%)	99.62

NAGU 2020017 was published on November 6, 2020 at 16:50 UTC for an event that occurred on November 9, 2020 at 06:18 UTC. The NAGU warned users about the unavailability of service by GSAT0101 for all signals. Since this NAGU was planned and published over 24 hours before the event, it was published in a timely manner.

NAGU 2020021 was published on December 14, 2020 at 14:00 UTC for an event that occurred at 06:12 on the same day. The NAGU alerted users ex post facto of the unavailability of service on all satellites for all signals. Since the NAGU was in regards to an unplanned event and was published within 72 hours of the occurrence, it was published in a timely manner.

The F/NAV signal broadcasted a SISA index of 255 from December 7, 2020 at 09:13 UTC until December 9, 2020 at 01:41 UTC on E01 (GSAT0210). Since users were protected with the status of the broadcast SIS, this was not considered an outage in the satellite service. Therefore, no NAGU was published.

Table 6-5 provides the timeliness details of each NAGU that occurred during this quarter.

Table 6-5. Summary of Q4 Published NAGUs

Month	NAGU Type	NAGU Number	Published	Event Time	Category	Timeliness	Description
Oct	NO NAGUS PUBLISHED						
Nov	PLN_OUTAGE	2020017	06 Nov 2020 16:50 UTC	09 Nov 2020 05:05 UTC	Planned	NAGU was published 56.25 hours before the event.	Galileo satellite GSAT0101 (all signals) will be unavailable from 2020-11-09 beginning 05:05 UTC. Outage recovery estimated on 2020-11-11 11:35 UTC.
	USABLE	2020018	11 Nov 2020 16:45 UTC	09 Nov 2020 06:18 UTC		N/A	Galileo satellite GSAT0101 (all signals) is usable since/as of 2020-11-11 beginning 08:20 UTC. payload on RAFS clock. Galileo satellite GSAT0101 (all signals) was unavailable from 2020-11-09 beginning 06:18 UTC.
	USABINIT	2020019	30 Nov 2020 13:10 UTC	30 Nov 2020 08:32 UTC		N/A	Galileo satellite GSAT0201 (all signals) is usable since/as of 2020-11-30 beginning 08:32 UTC. GSAT0201 is positioned in slot EXT01 of the constellation. payload on PHM clock.
	USABINIT	2020020	30 Nov 2020 13:10 UTC	30 Nov 2020 08:32 UTC		N/A	Galileo satellite GSAT0202 (all signals) is usable since/as of 2020-11-30 beginning 08:32 UTC. GSAT0202 is positioned in slot EXT02 of the constellation. payload on PHM clock.

Month	NAGU Type	NAGU Number	Published	Event Time	Category	Timeliness	Description
Dec	GENERAL (NOTICE)	2020021	14 Dec 2020 14:00 UTC	14 Dec 2020 00:00 UTC	General	NAGU was published 14 hours after the event.	Users have experienced a service degradation on all Galileo satellites. signals did not meet the minimum performance levels defined in the Galileo open service definition document starting 2020.12.14 at 00:00 UTC ending 2020.12.14 at 06:12 UTC. All satellites providing nominal signals as of 2020.12.14 at 06:55 UTC. Nominal service has been resumed.

7. IGS DATA (POSITION ERRORS)

This section will be included in future reports.

8. 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
FAA	Federal Aviation Administration
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSA	Global Navigation Satellite Systems Agency
GST	Galileo System Time
HDOP	Horizontal dilution of precision
HPE	Horizontal position error
IGS	International GNSS Service
IOC	Initial operational capability
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
RCA	Radial, along-track, and cross-track
RINEX	Receiver Independent Exchange
SDD	Service Definition Document
SHS	Signal Health Status
SIS	Signal-in-space
SISA	Signal-in-space accuracy
SISRA	Signal-in-space ranging accuracy
SISRE	Signal-in-space range error
SP3	Standard Product #3
SPS	Standard Positioning Service
SVID	Space Vehicle Identification
UPE	User Projected Error
USNO	United States Naval Observatory
UT	Universal Time

UTC	Universal Time Coordinated
UTC OE	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

9. REFERENCES

1. The European Space Agency, “What is Galileo?,” https://www.esa.int/Applications/Navigation/Galileo/What_is_Galileo, last accessed on February 23, 2021.
2. European GNSS (Galileo) Open Service Service Definition Document, Issue 1.1, available at https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo-OS-SDD_v1.1.pdf, published May 2019.
3. European Global Navigation Satellite Systems Agency, European GNSS Service Center, “NAGUs (Notice Advisory to Galileo Users),” <https://www.gsc-europa.eu/system-status/nagu-information>, last accessed March 31, 2021.
4. The European Space Agency, “Galileo Navigation Signals and Frequencies,” https://www.esa.int/Applications/Navigation/Galileo/Galileo_navigation_signals_and_frequencies, last accessed February 23, 2021.
5. European Global Navigation Satellite Systems Agency, <https://www.gsa.europa.eu/>, last accessed March 31, 2021.
6. European Global Navigation Satellite Systems Agency, European GNSS Service Center, “Almanac,” <https://www.gsc-europa.eu/product-almanacs>, last accessed March 31, 2021.
7. National Aeronautics and Space Administration, CDDIS, “GNSS MGEX Data,” https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/gnss_mgex.html, last accessed on March 15, 2021.
8. International GNSS Service, “MGEX Pilot Project,” <https://www.igs.org/mgex/#referencing>, last accessed on March 15, 2021.
9. International GNSS Service, “MGEX Data & Products,” <https://www.igs.org/mgex/data-products/#products>, last accessed March 15, 2021.
10. National Aeronautics and Space Administration, CDDIS, <https://cddis.nasa.gov/>, last accessed June 2, 2020.
11. L. Heng, "Safe Satellite Navigation with Multiple Constellations: Global Monitoring of GPS and GLONASS Signal-in-Space Anomalies," 2012.
12. Walter, T., Gunning, K., Phelts, E., and Blanch, J., “Validation of Unfaulted Error Bounds for ARAIM,” NAVIGATION Journal of The Institute of Navigation, February 2018.
13. Naval Oceanography Portal, “The United States Naval Observatory,” <https://www.usno.navy.mil/USNO>, last accessed March 31, 2021.