GLOBAL POSITIONING SYSTEM (GPS) PERFORMANCE

QUARTERLY REPORT 4 (OCTOBER TO DECEMBER 2022)

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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

1. INTRODUCTION

1.1. PURPOSE

This document presents the results of the GPS SPS performance assessment for the period of October to December 2022. The objectives of the study are to compare the measured performance against US DoD SPS performance specification [RD.1], covering the following parameters [AD.1]:

- SPS SiS Accuracy,
- SPS SiS Integrity,
- SPS SiS Continuity,
- SPS SiS Availability,
- PDOP Availability,
- SPS Position Service Availability and
- SPS Position Service Accuracy.

It also includes NANU analysis. The performance is analysed using raw data recorded at the OSi site MLG1.

1.2. DOCUMENT OVERVIEW

This document is arranged in the following sections:

- **Section 1**, the current section, describes the purpose, scope and structure of the document and lists the reference documents.
- **Section 2** gives an introduction to the activity, including performance specification and assessment methodology and assumptions;
- **Section 3** contains an assessment of performance against GPS SPS performance standards;
- **Section 4** provides an analysis of the NANUs;
- **Section 5** contains the conclusions.

1.3. REFERENCES

1.3.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.x]:

Table 1-1 Applicable Documents

Ref.	Title	Code	Version	Date
[AD.1]	Agreement relating to the provision of services pursuant to request for tenders for the provision of GNSS monitoring services	-	-	25/06/19
[AD.2]	19/02 - GNSS Monitoring Services – Contract Extension	-	-	May 22
[AD.3]				
[AD.4]				

1.3.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.x]:

Table 1-2 Reference Documents

Ref.	Title	Code	Version	Date
[RD.1]	Global Positioning System Standard Positioning Service Performance Standard	GPS SPS	5th Edition	Apr 2020
[RD.2]	Global Positioning System (GPS) Civil Monitoring Performance Specification	DOT-VNTSC-FAA-09-08	-	April 30th 2009
[RD.3]	Reference Set of Parameters for RAIM Availability Simulations', EUROCAE WG-62	-	-	8-9 July 2003

1.4. ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-3 Acronyms

Acronym	Definition
AOD	Age Of Data
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HDOP	Horizontal Dilution Of Precision
IAA	Irish Aviation Authority
IGS	International GNSS Service
NANU	Notice Advisory to Navstar Users
NOTAM	Notice To Airmen
PDOP	Position Dilution Of Precision
RAIM	Receiver Autonomous Integrity Monitoring
SIS	Signal In Space
SPS	Standard Positioning Service
TTA	Time To Alarm
UERE	User Equivalent Range Error
URA	User Range Accuracy
URE	User Range Error
VDOP	Vertical Dilution Of Precision

2. INTRODUCTION

2.1. PURPOSE

The purpose of the performance monitoring activity is to collect and analyse data on the performance of the GPS Signal in Space (SIS) [AD.1]. For this report, the applicable requirements are defined in the Global Positioning System Standard Positioning Service Performance Standard (GPS SPS PS), approved by the US Department of Defence [RD.1].

2.2. PERFORMANCE SPECIFICATION AND DEFINITIONS

The applicable performance specifications for the Standard Positioning Service [RD. 1] are as follows, with changes to the previous version of the GPS performance spec (prior to April 2020) noted:

Criteria	Specifications
SPS SIS Accuracy	**The User Range Error (URE) for any healthy satellite for Single-Frequency C/A-Code**: • ≤7.0 m 95% Global Average URE during Normal Operations over all age of data (AODs) ***[previous value was 7.8m]*** • ≤3.8m 95% Global Average URE during Normal Operations at Zero AOD ***[previous value was 6.0m]*** • ≤9.7 m 95% Global Average URE during Normal Operations at Any AOD ***[previous value was 12.8m]*** • ≤30 m 99.94% Global Average URE during Normal Operations over one-year period • ≤30 m 99.79% Worst Case Single Point Average URE during Normal Operations over one-year period • ≤388 m 95% Global Average URE during Extended Operations after 14 Days without Upload. **The User Range Error (URE) for all healthy satellites for Single-Frequency C/A-Code**: • ≤2.0 m 95% Global Average URE during Normal Operations over all age of data (AODs) ***[New specification – did not appear previously]*** **The User Range Rate Error (URRE) for Single-Frequency C/A-Code:** ≤0.006 m/sec 95% Global Average URRE over any 3-second interval during Normal Operations at Any AOD **The User Range Acceleration Error (URAE) for Single-Frequency C/A-Code:** ≤0.002 m/sec/sec 95% Global Average URAE over any 3-second interval during Normal Operations at Any AOD **The UTC Offset Error for Single-Frequency C/A-Code:** ≤30 nsec 95% Global Average UTCOE during Normal Operations at Any AOD ***[previous value was 40nsec]***
SPS SIS Integrity	**The SIS Instantaneous URE Integrity for Single-Frequency C/A-Code:**

Criteria	Specifications
	• ≤1x10^{-5} Probability Over Any Hour of the SPS SIS Instantaneous URE Exceeding the NTE Tolerance Without a Timely Alert during Normal Operations **The SIS Instantaneous UTCOE Integrity for Single-Frequency C/A-Code:** • ≤1x10^{-5} Probability Over Any Hour of the SPS SIS Instantaneous UTCOE Exceeding the NTE Tolerance Without a Timely Alert during Normal Operations **The SIS Instantaneous Psat and Pconst for Single-Frequency C/A-Code:** • ≤1x10^{-5} Fraction of Time when the SPS SIS Instantaneous URE Exceeds the NTE Tolerance Without a Timely Alert (Psat) ***[New specification – did not appear previously]*** • ≤1x10^{-8} Fraction of Time when the SPS SIS Instantaneous URE from two or more satellites Exceeds the NTE Tolerance due to a common cause Without a Timely Alert (Pconst) ***[New specification – did not appear previously]***
SPS SIS Continuity	**SPS SIS Unscheduled Failure Interruption Continuity** • ≥ 0.9998 Probability Over Any Hour of Not Losing the SPS SIS Availability from a Slot Due to Unscheduled Interruption • Given that the SPS SIS is available from the slot at the start of the hour
Status and Problem reporting	**Scheduled Event Affecting Service** • Appropriate NANU issued to the Coast Guard and the FAA at least 48 hours prior to the event for 95% of the events ***[previously did not specify a %]***
SPS SIS Availability	**SPS SIS Per-Slot Availability** • ≥ 0.957 Probability that a Slot in the Baseline 24-Slot Configuration will be Occupied by a Satellite Broadcasting a Healthy SPS SIS • ≥ 0.957 Probability that a Slot in the Expanded Configuration will be Occupied by a Pair of Satellites Each Broadcasting a Healthy SPS SIS **SPS SIS Constellation Availability** • ≥ 0.98 Probability that at least 21 Slots out of the 24 Slots will be Occupied Either by a Satellite Broadcasting a Healthy SPS SIS in the Baseline 24-Slot Configuration or by a Pair of Satellites Each Broadcasting a Healthy SPS SIS in the Expanded Slot Configuration • ≥ 0.99999 Probability that at least 20 Slots out of the 24 Slots will be occupied either by a Satellite Broadcasting a Healthy SPS SIS in the Baseline 24-Slot Configuration or by a Pair of Satellites Each Broadcasting a Healthy SPS SIS in the Expanded Slot Configuration. • ≥ 0.95 Probability that the Constellation will have at least 24 Operational Satellites regardless of Whether Those Operational Satellites are Located in Slots or Not.
PDOP Availability	• ≥ 98% global Position Dilution of Precision (PDOP) of 6 or less • ≥ 88% worst site PDOP of 6 or less
SPS Position Service Availability	• ≥ 99% Horizontal Service Availability average location • ≥ 90%Horizontal Service Availability worst-case location

Criteria	Specifications
	• ≥ 99% Vertical Service Availability average location • ≥ 90% Vertical Service Availability worst-case location **With 15 m horizontal and 33 m vertical (SIS only) 95% threshold over 24hours** ***[previous values were 17m and 37m]***
Positioning Accuracy	• ≤ 8 meters 95% Global Average Horizontal Error ***[previous value was 9m]*** • ≤ 15 meters 95% worst site Horizontal Error ***[previous value was 17m]*** • ≤ 13 meters 95% Global Average Vertical Error ***[previous value was 15m]*** • ≤ 33 meters 95% worst site Vertical Error ***[previous value was 37m]*** • Global Average Velocity Accuracy • ≤ 0.2 m/sec 95% velocity error, any axis ***[New specification – did not appear previously]*** • ≤ 30 nanoseconds time transfer error 95% of time for Time Transfer Domain Accuracy ***[previous value was 40nsec]***

Table 2-1: SPS Criteria and Specifications

The definitions for each of the criteria and the methodology used for assessment are given below. As well as the GPS SPS [RD.1], the GPS civil monitoring performance specification [RD.2] has also been used to help define the methodology for the assessment.

SPS SIS Accuracy

The SPS SIS accuracy is described in two statistical ways; one way is as the 95th percentile (95%) SPS SIS user range error (URE) at a specified age of data (AOD), the other is as the 95% SPS SIS URE over all AODs. With either statistical expression, the SPS SIS accuracy is also known as the SPS SIS pseudorange accuracy. In this context, "pseudorange" means the full pseudorange data set (i.e., the matched combination of a corrected pseudorange measurement and a pseudorange origin, or equivalently the matched combination of a raw pseudorange measurement and the associated NAV data).

Other accuracy-related SPS SIS performance parameters include the SPS SIS pseudorange rate (velocity) accuracy defined as the 95% SPS SIS pseudorange rate error over all AODs and the SPS SIS pseudorange acceleration (rate rate) accuracy defined as the 95% SPS SIS pseudorange acceleration error over all AODs. These values are not monitored as part of this performance monitoring contract.

SPS SIS Integrity

The SPS SIS integrity is defined as the trust which can be placed in the correctness of the information provided by the SPS SIS. SPS SIS integrity includes the ability of the SPS SIS to provide timely alerts to receivers when the SPS SIS should not be used for positioning or timing. The SPS SIS should not be used when it is providing misleading signal-in-space information (MSI), where the threshold for "misleading" is a not-to-exceed (NTE) tolerance on the SIS URE. For this SPS PS, the four components of integrity are the probability of a major service failure, the time to alert, the SIS URE NTE tolerance, and the alert (either one or the other of two types of alerts).

- Probability of a Major Service Failure. The probability of a major service failure for the SPS SIS is defined to be the probability that the SPS SIS instantaneous URE exceeds the SIS URE NTE tolerance (i.e., MSI) without a timely alert being issued (i.e., unalerted MSI [UMSI]). Alerts generically include both alarms and warnings.

- Time to Alert. The time to alert (TTA) for the SPS SIS is defined to be the time from the onset of MSI until an alert (alarm or warning) indication arrives at the receiver's antenna. Real-time alert information broadcast as part of the NAV message data is defined to arrive at the receiver's antenna at the end of the NAV message subframe which contains that particular piece of real-time alert information.
- SIS URE NTE Tolerance. The SPS SIS URE NTE tolerance for a healthy SPS SIS is defined to be 4.42 times the upper bound on the URA value corresponding to the URA index "N" currently broadcast by the satellite. The SIS URE NTE tolerance for a marginal SPS SIS is not defined and there is no SIS URE NTE tolerance for an unhealthy SPS SIS.

SPS SIS Continuity

The SPS SIS continuity for a healthy SPS SIS is the probability that the SPS SIS will continue to be healthy without unscheduled interruption over a specified time interval. Scheduled interruptions which are announced at least 48 hours in advance do not contribute to a loss of continuity. Scheduled SPS SIS interruptions are announced by way of the Control Segment issuing a "Notice Advisory to Navstar Users" (NANU). NANUs are similar to the "Notices to Airmen" (NOTAMs) issued regarding scheduled interruptions of ground-based air navigation aids. OCS internal procedures are to issue NANUs for scheduled interruptions at least 96 hours in advance.

SPS SIS Availability

The SPS SIS availability is the probability that the slots in the GPS constellation will be occupied by satellites transmitting a trackable and healthy SPS SIS. For this SPS Performance Standard, there are two components of availability as follows:

- Per-Slot Availability. The fraction of time that a slot in the GPS constellation will be occupied by a satellite that is transmitting a trackable and healthy SPS SIS.
- Constellation Availability. The fraction of time that a specified number of slots in the GPS constellation

PDOP Availability

PDOP availability is defined as the percentage of time over a specified time interval that the predicted PDOP is less than a specified value for any point within the service volume [RD.1].

Position Service Availability

Position service availability is defined as the percentage of time over a specified time interval that the position accuracy is less than a specified value for any point within the service volume [RD.1].

Positioning Service Accuracy

Position service accuracy is defined as the statistical difference between position measurements and a surveyed benchmark for any point within the service volume over a specified time interval [RD.1].

2.3. METHODOLOGY

For the performance analysis in this report, raw GPS measurement data from reference stations has been analysed. The primary source of data is the OSi network of active stations in Ireland. OSi operates a national network of GNSS receiver stations. The network consists of 25 receivers that provide 24-hour availability of dual frequency GPS and GLONASS data. For the purposes of this performance monitoring activity, OSi provides raw data for 2 of these sites to GMV NSL for processing and analysis. The sites that are used are Mullingar (MLG1) and Sligo Hospital (SLGO). The locations of these sites are shown in Figure 2-1.

Figure 2-1: Location of Performance Monitoring Stations

In this report, MLG1 is used as the main site to provide performance monitoring across the whole of Irish airspace and SLGO is a back-up in case of problems with MLG1 and to allow cross-checking of performance in the case of anomaly investigations. These sites have been chosen to fulfil the following criteria:

Centrally located within Ireland in order to ensure monitoring of complete airspace;

Good data availability and continuity (i.e. avoid sites with historically poor data availability);

Good measurement quality (i.e. avoid sites with known interference, multipath or sky visibility issues);

Availability of required observation types and data.

In addition to the raw data, NANU information is downloaded from the US Coast Guard Navigation Centre website (http://www.navcen.uscg.gov/?pageName=gpsNanuInfo). This provides information on the NANUs for scheduled and unscheduled outages during the monitoring period.

The methods for assessing of each of the requirements are described below.

SPS SIS Accuracy

SIS accuracy is assessed through processing and analysis of the raw measurement data. In order to compute the SIS accuracy, the measurements recorded at the GPS receiver are used to compute the instantaneous SIS errors. This is done by computing the difference between computed ranges (based on known receiver location and satellite position) and the corrected measurement, which has satellite and receiver clock biases, group delay, ionospheric and tropospheric errors removed. Once the SIS range errors for every satellite measurement on every epoch have been computed, the per-satellite and all satellite statistics across the whole period, as well as daily statistics for all satellites combined, are generated.

SPS SIS Integrity

SIS accuracy is assessed through processing and analysis of the raw measurement data. The SIS integrity is assessed by comparing each instantaneous computed SIS error value with a threshold value of 4.42 x broadcast URA. The number of occasions where the instantaneous URE exceeds the threshold are counted and checked against the expected number of failures.

SPS SIS Continuity

SIS continuity is assessed through analysis of the broadcast navigation messages and the NANU archive. Firstly, the daily broadcast navigation messages are scanned in order to find the time periods for any satellites that do not have healthy navigation messages. These satellites and time periods are then matched against NANU information to see if the outages are scheduled or unscheduled.

The SIS continuity is computed for the baseline 24-slot constellation and is an average value over all slots. The total time that any satellites in the baseline constellation were unhealthy due to an unscheduled outage is divided by the total time in the analysis period and expressed as a percentage. Results are presented for the reporting period and, when available, for the previous year.

SPS SIS Availability

SIS availability is assessed through analysis of the broadcast navigation messages and the NANU archive. Firstly, the daily broadcast navigation messages are scanned in order to find the time periods for any satellites that do not have healthy navigation messages. These satellites and time periods are then matched against NANU information to see if the outages are scheduled or unscheduled.

The SIS availability is computed for the baseline 24-slot constellation as well as for the whole constellation and is an average value over all slots. At each epoch the number of healthy satellites (both in the baseline 24-slot constellation and in total) is counted. Then the following parameters are computed:

- Total time that there are less than 21 healthy satellites in the baseline constellation;
- Total time that there are less than 20 healthy satellites in the baseline constellation;
- Total time that there are less than 24 healthy satellites in the whole constellation.

These parameters are then divided by total time of the analysis and expressed as percentage values. Results are presented for the reporting period and, when available, for the previous year.

It should be noted that in case the baseline 24-slot constellation does not meet requirements, the analysis will be expanded to include pairs of satellites in the expanded slot constellation.

PDOP Availability

PDOP availability is assessed through processing and analysis of the raw measurement data. The PDOP availability is assessed by computing the PDOP for all satellites in view above 5 degrees at the GPS receiver at every epoch (1Hz rate). Each PDOP value is checked against the threshold value of 6 and any failures are counted. The numbers of failures on each day are then used to generate the daily availability value. A separate availability value for each day is computed.

Position Service Availability

Position service availability is assessed through processing and analysis of the raw measurement data. The derivation of the position service availability requirements of 15m (95% horizontal accuracy) and 33m (95% vertical accuracy) for 99% of the time are explained a bit more in section B.3.2 of the GPS SPS [RD.1]. The requirement is based on fulfilling a 1-sigma UERE of 3.6m, HDOP of 2.1 and VDOP of 4.53. To check this requirement, the following approach is used:

- For each day, compute daily rms SIS error for all satellites combined. This is equivalent to the 1-sigma UERE in the description above;

- On each epoch, multiply daily rms SIS error by HDOP value to compute estimated horizontal accuracy due to SIS error;
- For each epoch, multiply daily rms SIS error by VDOP value to compute estimated vertical accuracy due to SIS error;
- Compute daily availability (%) of estimated horizontal accuracy < 7.5m (1-sigma);
- Compute daily availability (%) of estimated vertical accuracy < 16.5m (1-sigma).
- If daily availability of horizontal accuracy greater than the required threshold, the requirement for horizontal service accuracy is passed;
- If daily availability of vertical accuracy greater than the required threshold, the requirement for vertical service accuracy is passed.

Positioning Service Accuracy

In order to check the position service accuracy, the raw measurements recorded at the GPS receiver are used to compute a user position solution on every epoch (1Hz). The computed positions are then compared against the known position of the receiver in order to generate horizontal and vertical position errors. Statistics for 95% error value, 99.99% error value etc. are then computed separately for each day and checked against the thresholds.

2.4. ASSUMPTIONS

For processing the raw data and generating the results the following assumptions are made:

- Single frequency (L1) processing with C/A code;
- 5-degree elevation mask used;
- Broadcast iono model (Klobuchar) used to remove ionospheric errors;
- RTCA trop model used to remove tropospheric errors;
- Weighted least squares RAIM algorithm used for RAIM prediction (protection level computation) and Fault Detection;
- Probability of missed detection = 0.001 and Probability of false alarm = 1x10-5 for RAIM computations;
- UERE budget (non-SIS components) used in position solution and for RAIM predictions based given below [RD.3]:

Elevation, degrees	Error, metres
5	7.48
10	6.64
15	5.92
20	5.31
30	4.31
40	3.57
50	3.06
60	2.73
90	2.44

- The URA value from the broadcast navigation message is combined with the values in the table to form the total UERE for the observations.

As the actual monitoring is based on the measurements from one receiver, the following points should be noted:

- Performance monitoring is local to the monitoring station with a coverage area defined by the correlation of the major error sources and the configuration of the constellation.
- The range domain errors contain the residuals of other error sources other than the SIS range errors, hence the performance statistics generated are conservative.

3. SPS PERFORMANCE

3.1. BASELINE 24-SLOT CONSTELLATION

The SPS SIS performance standard is largely based on the GPS baseline 24-slot constellation, which consists of 24 slots in six orbital planes with four slots per plane. Some of these slots are expanded, whereby two satellites occupy fore and aft positions at that slot, in which case the slot is occupied as long as at least one of the expanded slots is occupied by an operational satellite. It is important to identify the baseline constellation (and expanded slots) to act as reference to subsequent data processing and analysis. The following tables show the satellite PRN in each slot for the baseline constellation for the period October to December 2022[1].

Table 3-1: Baseline constellation in the Period 1 October to 31 December 2022

Slot	A1	A2	A3	A4	B1A/B1F	B2	B3	B4	C1	C2	C3	C4A/C4F
PRN	24	31	30	7	16/26	25	14	12	29	27	8	19/17
Slot	D1	D2A/D2F	D3	D4	E1	E2	E3A/E3F	E4	F1	F2A/F2F	F3	F4
PRN	11	1/21	18	6	3	10	5/20	23	32	15/13	9	4

Note that in the latest version of the GPS SPS performance spec [RD.1] there are additional expandable slots defined for A2 but these are not currently used.

3.2. SPS SIS ACCURACY

In addition to the specifications in Table 2-1, the Conditions and Constraints for SPS SIS URE Accuracy specification [RD.1] are:

- For any healthy SPS SIS
- Neglecting single-frequency ionospheric delay model errors
- Including group delay time correction (TGD) errors at L1
- Including inter-signal bias (P(Y)-code to C/A-code) errors at L1

The statistics presented here are based on the same sample rate for positioning (1Hz). It should be noted that the computed range errors (in addition to SIS errors) contain residual errors local to the monitoring antenna (multipath, tropospheric and ionospheric). The URE Accuracy (95th percentile) values of each satellite for the period October to December 2022 are shown in the next figure.

[1] The information on slots is taken from the figure at https://www.navcen.uscg.gov/pdf/gps/current.pdf. It is noted that there is some inconsistency between this figure and the slot numbers in the ops advisory messages. The figure was last updated on 1st June 2022, and previously before that on 1st Feb 2021.

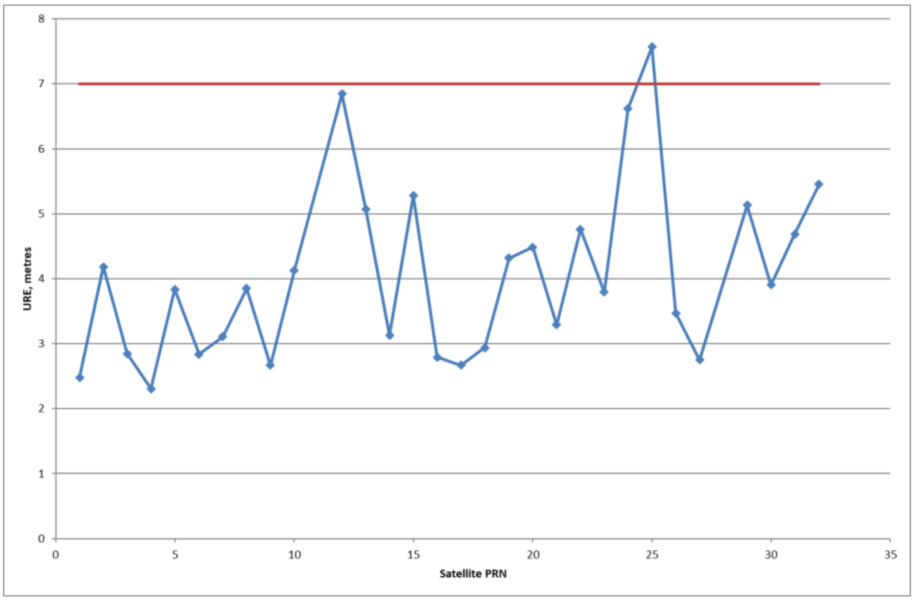

Figure 3-1: Constellation URE (95%) for Reporting Period

It can be seen that the URE (95%) for most satellites is below the 7m threshold but there are two very close to the limit and one that exceeds the threshold. This could indicate a failure against this requirement. However, further analysis (as shown in Annex A) suggests these apparently high errors are most likely due to larger than usual residual ionospheric errors and therefore should not be counted as a failure because the requirement of 7m is for signal in space errors only and not atmospheric effects.

The daily constellation RMS URE results in the period October to December 2022 and the 3.6m threshold are shown in the next figure. Note that ≤ 7 m 95% SPS SIS URE performance standard is equivalent to a ≤ 3.6 m RMS SPS SIS URE performance standard [RD.1]. This is also important for the position service availability assessment.

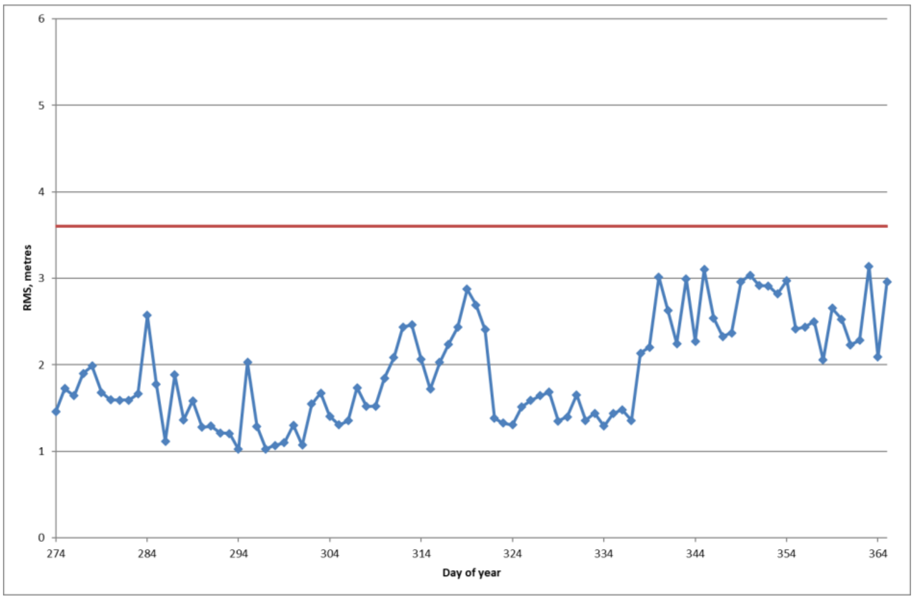

Figure 3-2: Constellation RMS URE for Reporting Period

It can be seen that the RMS values are below the threshold (3.6 metres) on all days, although they are higher than usual towards the end of the period (as discussed further in Annex A).

As well as the 95% and rms URE statistics, additional URE statistics are computed, including mean, 1-sigma and maximum values. Although not strictly required for the performance specification, these values can be useful for anomaly investigation. The range error statistics (in metres) for the period October to December 2022 are given in the table below.

Table 3-2: Range Error Statistics for Reporting Period

PRN	Range Error (mean)	Range Error (RMS)	1-sigma	Range Error (95%)	Range Error (max)	Number of Samples
1	0.43	1.39	1.32	2.48	12.62	2409391
2	1.57	2.18	1.51	4.18	7.36	2967064
3	0.21	1.45	1.43	2.85	6.83	2537679
4	-0.14	1.16	1.16	2.31	6.64	2782780
5	0.73	1.88	1.74	3.84	11.22	2716390
6	0.00	1.50	1.50	2.84	8.54	2768663
7	0.19	1.45	1.44	3.11	8.13	2881043
8	0.51	1.95	1.88	3.85	15.23	2508194
9	0.13	1.38	1.37	2.67	8.54	2605703
10	1.45	2.03	1.42	4.13	11.00	2920403
11	0.36	1.57	1.53	3.07	8.73	2838537
12	1.91	3.19	2.56	6.84	11.18	2541755
13	1.33	2.50	2.11	5.07	8.68	2296790
14	0.22	1.43	1.42	3.13	10.02	2897118
15	1.38	2.53	2.12	5.28	9.45	2399846
16	0.81	1.53	1.29	2.79	7.97	2632585
17	0.48	1.36	1.27	2.67	8.14	2889005
18	0.78	1.47	1.25	2.94	7.52	2854208
19	1.43	2.03	1.45	4.32	8.39	2856117
20	1.12	2.23	1.94	4.49	8.96	2639344
21	1.87	2.13	1.02	3.29	11.46	2290341
22	1.26	2.07	1.64	4.76	7.74	2947251
23	0.89	1.69	1.43	3.79	8.05	2891486
24	2.49	3.31	2.19	6.62	10.01	2115833
25	2.52	3.50	2.43	7.57	10.86	2193551
26	1.02	1.71	1.37	3.47	6.37	2435648
27	1.17	1.68	1.20	2.75	9.28	2324331
29	1.25	2.34	1.98	5.13	9.21	2715052
30	0.75	1.91	1.76	3.91	7.10	2698994
31	1.10	2.06	1.74	4.69	8.20	2663749
32	1.34	2.29	1.86	5.45	9.79	2884694
All	0.87	1.82	1.60	4.20	15.23	82103545

Overall, the measured SIS accuracy for any satellite is below the threshold values throughout the monitoring period for most satellites – reasons for higher values are discussed in Annex A.

The measured accuracy for all satellites combined is well above the threshold of 2m, which again is discussed further in Annex A but is likely due to higher than usual ionospheric residual errors affecting the analysis.

3.3. SPS SIS INTEGRITY

In addition to the specifications in Table 2-1, the Conditions and Constraints for SPS SIS Integrity performance [RD.1] are:

For any healthy SPS SIS;

SPS SIS URE NTE tolerance defined to be ±4.42 times the upper bound on the URA value corresponding to the URA index "N" currently broadcast by the satellite;

Given that the maximum SPS SIS instantaneous URE did not exceed the NTE tolerance at the start of the hour;

Worst case for delayed alert is 6 hours;

Neglecting single-frequency ionospheric delay model errors.

Based on the requirement of $1x10^{-5}$/hr probability for misleading information, 92-day period and a 31-satellite constellation, the maximum number of events expected is 0.66.

On every epoch throughout the monitoring period, the instantaneous measured URE for each satellite has been compared against a threshold of 4.42 times the upper value of the URA index. The number of URE values above the threshold has been recorded and is checked against the expected number.

From the analysis there are 4 days where this condition is met, which could indicate a failure. However, looking at the events in more detail:

- On 7th November there is an issue flagged for 1251 seconds. The issue is raised for PRN08 after 14:18:30 and last until 14:37:11 when PRN08 drops below the elevation mask of 5 degrees. During this period PRN08 is at low elevation and at azimuth of around 10 degrees. Then at 14:46:06 PRN10 comes into view above 5 degrees at -32 degrees azimuth with residual that exceeds the threshold. This last until 14:48:16 as the satellite starts to climb higher and the residual error gradually reduces. Looking at SLG1 then there are also some high residuals for the same satellites and the same times, which could indicate a satellite problem. However, as both satellites are at low elevation the issue could be high ionospheric residuals. These satellites have also been checked at other sites in other countries where the satellites are at much higher elevation angles at those times, and ionospheric conditions are different, and the range errors are much smaller and within the threshold. This suggests the higher errors are due to ionospheric residuals rather than a satellite issue or the same problem would be seen at all locations.
- On 26th November there is an issue flagged for 1 second at 14:18:30 when PRN05 appears for one epoch at 7 degrees elevation with high residual error, and then disappears again. When it is tracked again a few seconds later the errors are much smaller. This appears to be a local issue – perhaps with multipath or tracking difficulties – because PRN05 is tracked at SLG1 at the same time and the errors are normal on that epoch.
- On 7th December there is an issue from 14:19:02 on PRN21, when it rises just above the 5 degree elevation mask, until 14:29:32 when it falls again below 5 degrees. Also, at 14:40:48 PRN01 appears above the 5 degree elevation mask with higher residual errors and lasts until 15:05:58 as the satellite starts to climb higher and the residual error gradually reduces. Looking at SLG1 then there are also some high residuals for the same satellites and the same times, which could indicate a satellite problem. However, as both satellites are at low elevation the issue could be high ionospheric residuals. These satellites have also been checked at other sites in other countries where the satellites are at much higher elevation angles at those times, and ionospheric conditions are different, and the range errors are much smaller and within the threshold. This suggests the higher errors are due to ionospheric residuals rather than a satellite issue or the same problem would be seen at all locations.
- On 11th December there is an issue flagged for PRN12 and PRN25 at 15:56:41 for a single epoch. This appears to be a local issue – perhaps with multipath or tracking difficulties – because PRN12 and 25 are tracked at SLG1 at the same time and the errors do not exceed the threshold on that epoch.

As these higher residual errors are related only to local effect and not system issues, they are not counted as SIS integrity failures and therefore this requirement is passed.

3.4. SPS SIS CONTINUITY

In addition to the specifications in Table 2-1, the Conditions and Constraints for SPS SIS Continuity performance [RD.1] are:

Calculated as an average over all slots in the 24-slot constellation, normalized annually;

Given that the SPS SIS is available from the slot at the start of the hour.

During this reporting period there was one unscheduled event affecting the baseline constellation, lasting for a total of 1.82 hours. Therefore this gives a continuity figure of 99.996% in this period, which does meet the requirement of 99.98% in this period.

3.5. SPS SIS AVAILABILITY

In addition to the specifications in Table 2-1, the Conditions and Constraints for SPS SIS Availability performance [RD.1] are:

Calculated as an average over all slots in the 24-slot constellation, normalized annually;

Applies to satellites broadcasting a healthy SPS SIS which also satisfy the other performance standards in this SPS Performance Standard.

The total period (in this monitoring period) in which satellites from the baseline 24-satellite constellation broadcast an unhealthy SIS was 129.75 hours. This is equivalent to an average of 0.99755 over all slots in the 24-slot constellation and satisfies SPS SIS Per-slot Availability standard (≥ 0.957).

The minimum number of the baseline constellation satellites broadcasting healthy SPS SIS was 22, greater than the specifications of 20 and 21. Hence, performance during the monitoring period was measured at the 100% level, satisfying the Performance Standard as specified below.

- ≥0.98 Probability that at least 21 Slots out of the 24 Slots will be Occupied Either by a Satellite Broadcasting a Healthy SPS SIS in the Baseline 24-Slot Configuration or by a Pair of Satellites Each Broadcasting a Healthy SPS SIS in the Expanded Slot Configuration;
- ≥ 0.99999 Probability that at least 20 Slots out of the 24 Slots will be occupied either by a Satellite Broadcasting a Healthy SPS SIS in the Baseline 24-Slot Configuration or by a Pair of Satellites Each Broadcasting a Healthy SPS SIS in the Expanded Slot Configuration.

The minimum number of operational satellites broadcasting healthy messages in this reporting period was 29. This represents performance at the 100% level, satisfying the Performance Standard as specified below.

- ≥ 0.95 Probability that the Constellation has at least 24 operational satellites regardless of whether the operational satellites are located in the baseline slots.

3.6. PDOP AVAILABILITY

In addition to the specifications in Table 2-1, the Conditions and Constraints for PDOP performance [RD.1] are:

Defined for position solution meeting the representative user conditions and operating within the service volume over any 24-hour interval;

Based on using only satellites transmitting standard code and indicating “healthy” in the broadcast navigation message.

The following plot shows the daily PDOP availability (PDOP < 6) calculated at the site for all healthy satellites above 5 degrees elevation during the period October to December 2022.

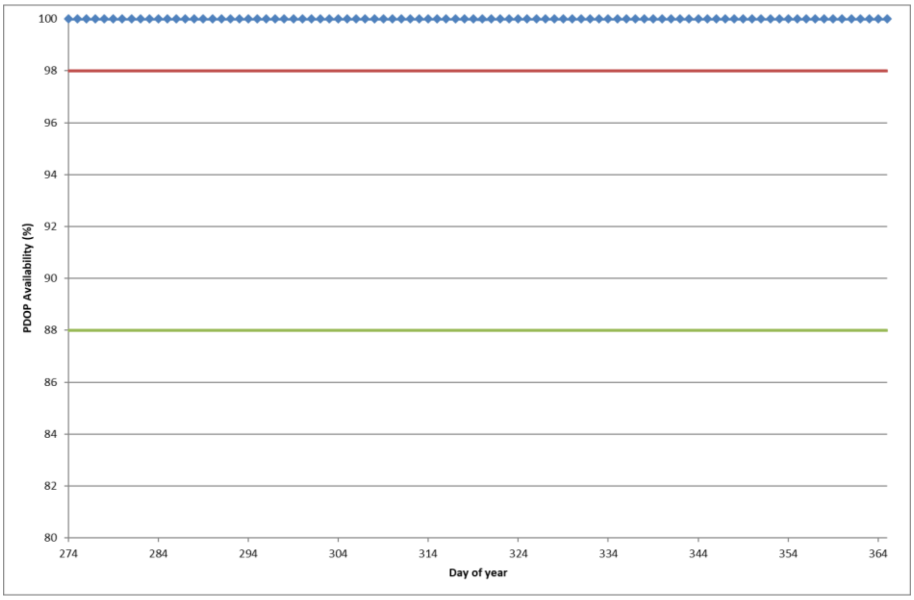

Figure 3-3: Daily PDOP Availability in the Reporting Period

It can be seen that the daily PDOP availability values are all above the thresholds of 98% (global average) and 88% (worst site). Therefore, the PDOP availability fulfils the requirements.

In addition, the daily mean and maximum PDOP values are displayed for the same period.

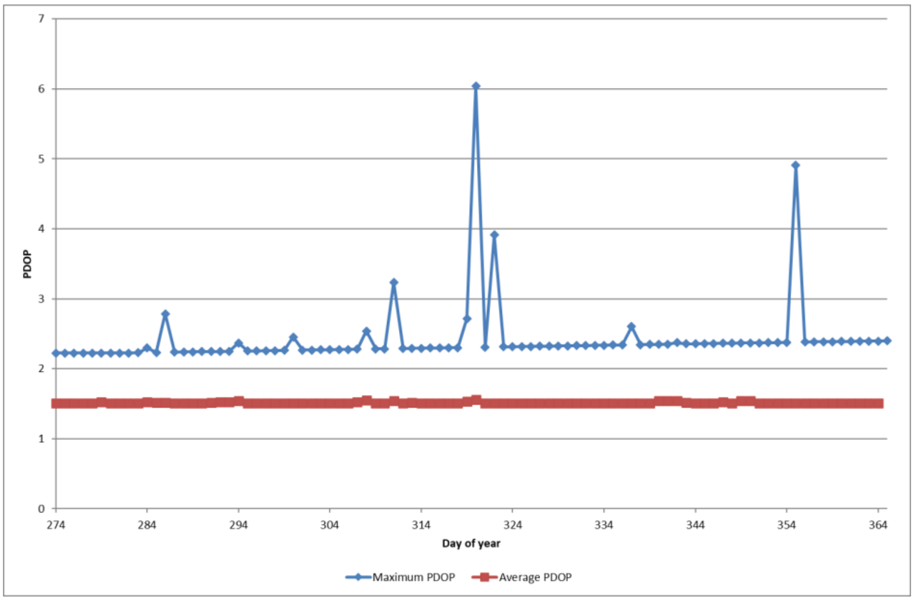

Figure 3-4: Daily Maximum PDOP Value in the Reporting Period

The daily PDOP values PDOP can be used to identify specific days that have different performance from the others. It can be seen that on some days the PDOP is higher than usual although always below 6. The days with highest maximum PDOP are those affected by short loss of tracking of multiple satellites (most likely due to local interference).

3.7. POSITION SERVICE AVAILABILITY

In addition to the specifications in Table 2-1, the Conditions and Constraints for Service Availability performance [RD.1] are:

15 meters horizontal (SIS only) 95% threshold;

33 meters vertical (SIS only) 95% threshold;

Defined for position solution meeting representative user conditions and operating within the service volume over any 24-hour interval;

Based on using only satellites transmitting standard code and indicating "healthy" in the broadcast navigation message.

The computation of these values is detailed in section 2.3.

The daily horizontal and vertical service availabilities for the period October to December 2022 are shown in the following figures.

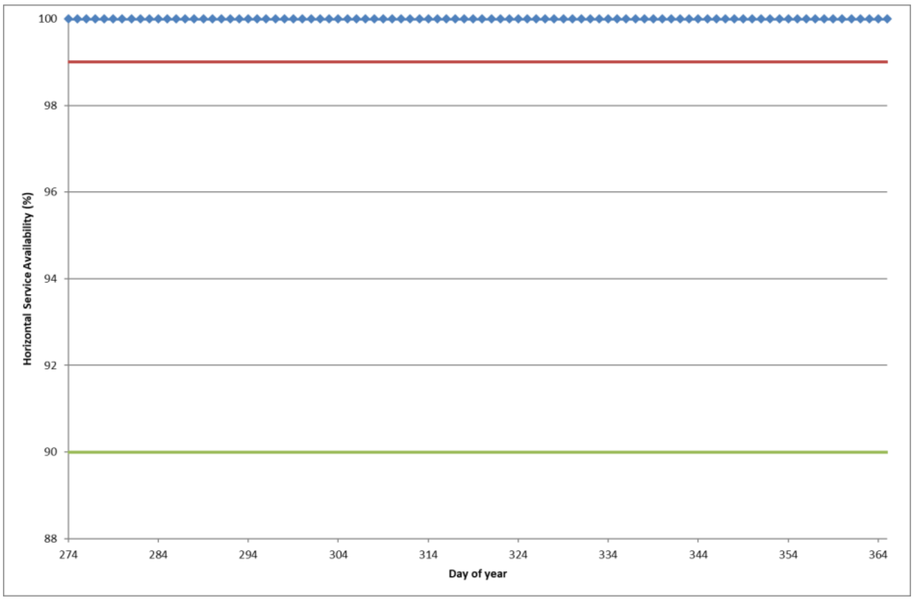

Figure 3-5: Daily Horizontal Service Availability Values for Reporting Period

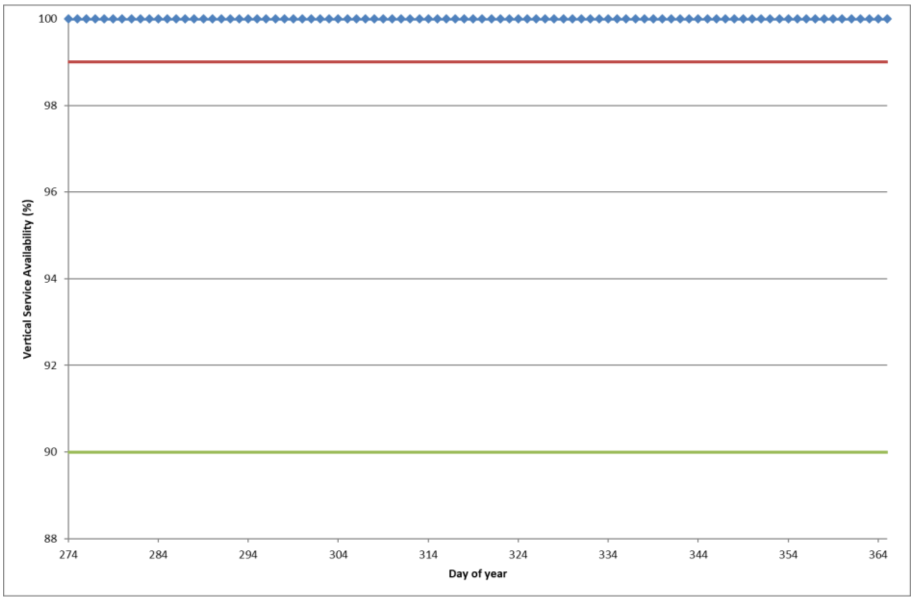

Figure 3-6: Daily Vertical Service Availability Values for Reporting Period

These plots show the horizontal and vertical availability are well above the thresholds of 99% (global average) and 90% (worst site) for the reporting period. Therefore, the position service availability fulfils the requirements.

3.8. POSITIONING ACCURACY

In addition to the specifications in Table 2-1, the Conditions and Constraints for Positioning Accuracy performance [RD.1] are:

Defined for position solution meeting the representative user conditions;

Standard based on a measurement interval of 24 hours averaged over all points within the service volume.

For this monitoring activity it should be noted that the position accuracy is assessed through analysis of real data at a single point, rather than through service volume analysis.

The daily horizontal and vertical accuracy values (95%) for the period October to December 2022 are shown in the following figures.

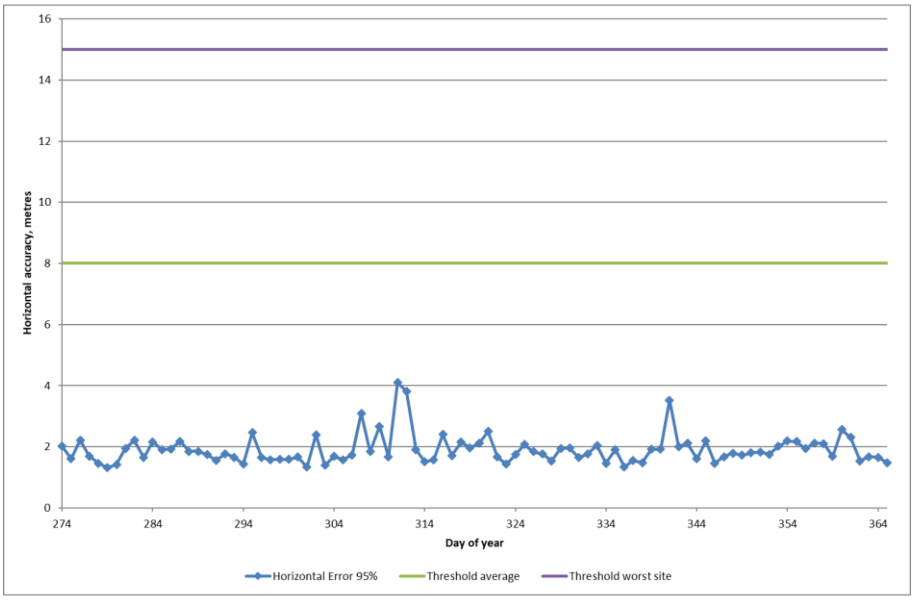

Figure 3-7: Daily Horizontal Position Accuracy (95%) for Reporting Period

It can be seen that the daily horizontal accuracy values are all below the thresholds of 8m (global average) and 15m (worst site).

Also, the daily vertical accuracy values are well below the thresholds of 13m (global average) and 33m (worst site).

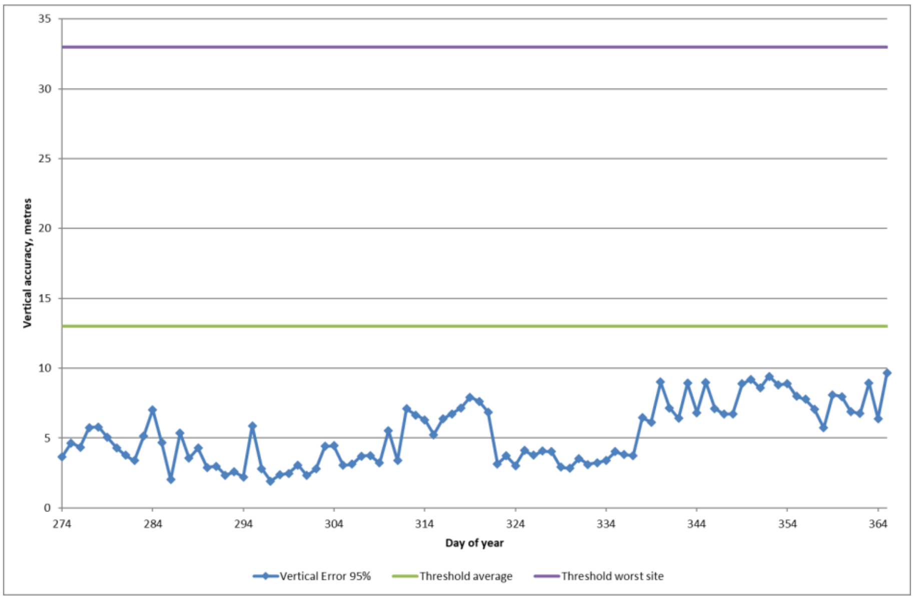

Figure 3-8: Daily Vertical Position Accuracy (95%) for Reporting Period

In addition, the daily position accuracy values at the 99.99% level are shown for the same period.

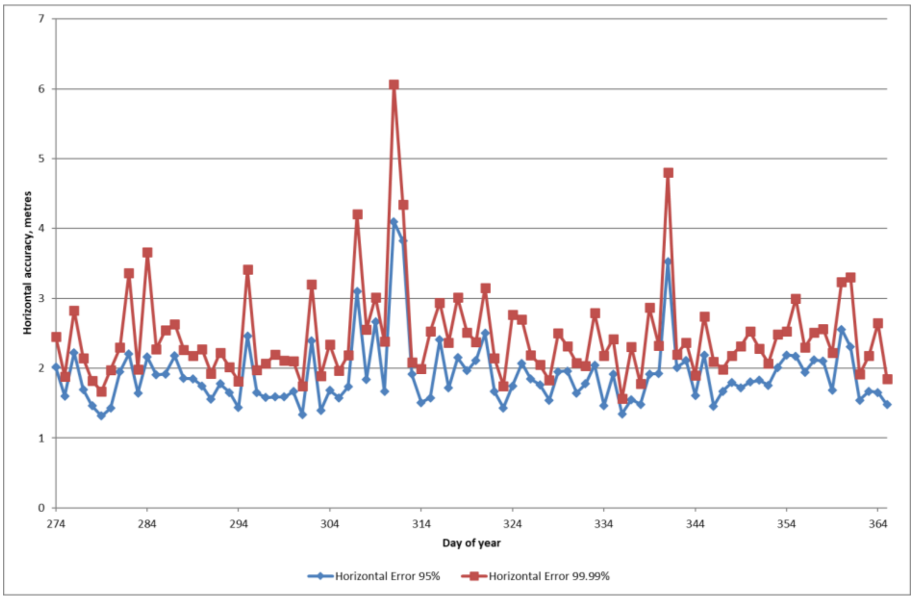

Figure 3-9: Daily Horizontal Position Accuracy (99.99%) for Reporting Period

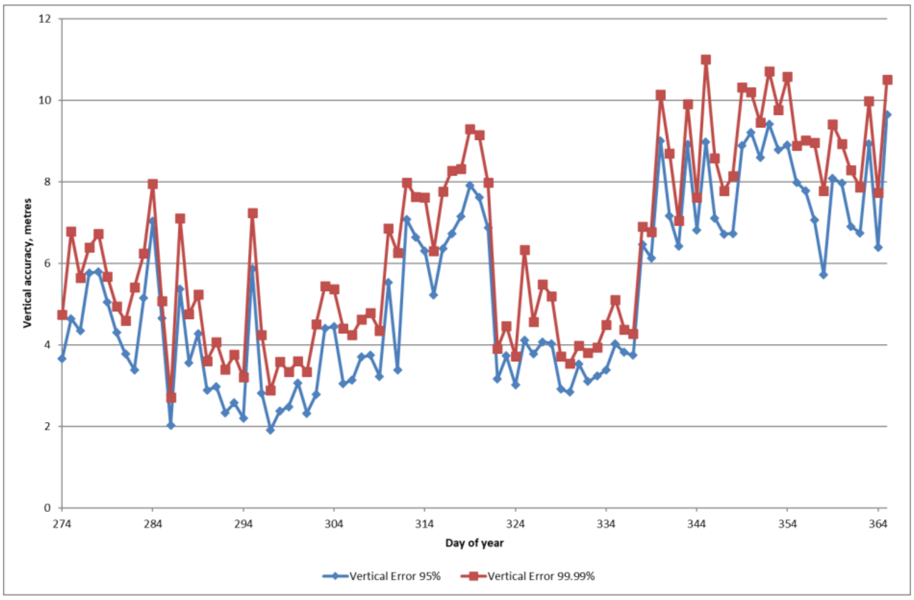

Figure 3-10: Daily Vertical Position Accuracy (99.99%) for Reporting Period

It can be seen that the 99.99% values generally follow the same pattern as the 95% values and are not significantly larger.

4. NANU ANALYSIS

(http://www.navcen.uscg.gov/?pageName=gpsNanuInfo). Summaries of the forecast and actual outages for scheduled and unscheduled events are given below. NANUs that affect a whole slot in the baseline constellation are highlighted in green. NANUs that affect one satellite of an expanded slot in the baseline constellation are highlighted in blue, tan, orange, red or purple.

Table 4-1: Summary of Forecast Scheduled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2022060	3	FCSTDV	279	1425	280	225	12	E1
2022062	25	FCSTMX	284	730	284	1400	6.5	B2
2022063	25	FCSTMX	285	730	285	1400	6.5	B2
2022064	32	FCSTMX	286	1430	286	2030	6	F1
2022068	32	FCSTEXTD	286	1430	UFN	NA	NA	F1
2022071	24	FCSTMX	291	1430	291	2000	5.5	A1
2022072	9	FCSTMX	291	2200	292	100	3	F3
2022073	3	FCSTMX	292	1900	292	2300	4	E1
2022074	27	FCSTMX	292	2230	293	300	4.5	C2
2022075	26	FCSTMX	293	2000	294	0	4	B1F
2022076	8	FCSTMX	294	0	294	400	4	C3
2022077	10	FCSTMX	294	1350	294	1700	3.5	E2
2022078	1	FCSTMX	294	1730	294	2130	4	D2A
2022088	30	FCSTMX	306	2355	307	1155	12	A3
2022089	12	FCSTMX	307	555	307	1755	12	B4
2022090	17	FCSTMX	308	0	308	1200	12	C4F
2022091	29	FCSTMX	308	845	308	2045	12	C1
2022092	5	FCSTMX	311	1130	311	1315	1.75	E3A
2022105	5	FCSTRESCD	311	1000	311	2200	12	2022092
2022093	15	FCSTMX	311	1315	311	1500	1.75	F2A
2022106	15	FCTSRESCD	311	1200	312	0000	12	2022093
2022094	31	FCSTMX	313	1945	313	2145	2	A2
2022107	31	FCSTRESCD	313	1945	314	0745	12	2022094
2022095	2	FCSTDV	314	100	315	100	24	D5
2022100	29	FCSTUUFN	308	843	NA	NA	NA	C1
2022110	7	FCSTMX	318	2200	319	1000	12	A4
2022111	6	FCSTMX	319	415	319	1615	12	D4
2022114	15	FCSTMX	320	1100	320	2300	12	F2A
2022118	31	FCSTMX	340	1000	341	1000	24	A2
2022119	26	FCSTMX	342	1300	343	1300	24	B1F
2022121	23	FCSTMX	347	1100	348	1100	24	E4

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2022122	19	FCSTDV	349	1730	350	530	12	C4A
2022125	19	FCSTRESCD	354	1645	355	0445	12	2022122
2022124	31	FCSTMX	349	1000	350	1500	29	A2

Table 4-2: Summary of Actual Scheduled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2022061	3	FCSTSUMM	279	1428	279	2019	5.85	2022061
2022066	25	FCSTSUMM	284	809	284	1309	5.0000	2022062
2022067	25	FCSTSUMM	285	802	285	1238	4.6000	2022063
2022069	32	FCSTSUMM	286	1523	286	2057	5.5667	2022068
2022079	24	FCSTSUMM	291	1452	291	1707	2.2500	2022071
2022080	9	FCSTSUMM	291	2220	292	6	1.7666	2022072
2022081	3	FCSTSUMM	292	1923	292	2055	1.5333	2022073
2022082	27	FCSTSUMM	292	2352	293	54	1.0333	2022074
2022083	26	FCSTSUMM	293	2144	293	2337	1.8833	2022075
2022084	8	FCSTSUMM	294	17	294	122	1.0833	2022076
2022085	10	FCSTSUMM	294	1418	294	1555	1.6166	2022077
2022087	1	FCSTSUMM	294	1803	294	1954	1.85	2022078
2022096	30	FCSTSUMM	307	19	307	155	1.6	2022088
2022097	12	FCSTSUMM	307	555	307	832	2.6166	2022089
2022098	17	FCSTSUMM	308	417	308	649	2.5333	2022090
2022108	5	FCSTSUMM	311	1008	311	1222	2.2333	2022105
2022109	15	FCSTSUMM	311	1211	311	1344	1.55	2022106
2022112	31	FCSTSUMM	313	1947	313	2056	1.15	2022107
2022113	2	FCSTSUMM	314	110	314	735	6.4166	2022095
2022115	7	FCSTSUMM	318	2200	319	315	5.25	2022110
2022116	6	FCSTSUMM	319	424	319	536	1.2	2022111
2022117	15	FCSTSUMM	320	1118	320	2020	9.0333	2022114
2022120	31	FCSTSUMM	340	1033	341	410	17.616	2022118
2022123	26	FCSTSUMM	342	1330	343	343	14.2166	2022119
2022126	23	FCSTSUMM	347	1100	347	2350	12.8333	2022121
2022128	19	FCSTSUMM	354	1744	354	2305	5.35	2022125
2022127	31	FCSTSUMM	349	1023	350	306	16.7166	2022124

Table 4-3: Summary of Cancelled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Ref
2022070	32	FCSTCANC	287	1430	287	2030	2022065

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Ref
2022099	29	FCSTCANC	308	0845	308	2045	2022091
2022102	29	FCSTCANC	308	0843	NA	NA	2022100

Table 4-4: Summary of Forecast and Actual Unscheduled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2022103	29	UNUNOREF	308	843	308	1032	1.816666667	C1

It is noted that the unscheduled outage was actually released to replace an erroneous scheduled outage. NANU 2022100 was a scheduled unusable NANU, that was apparently closed by 2022101. But this was cancelled by NANU 2022102 and the unscheduled 2022103 was released in its place.

The constellation availability and continuity figures for the baseline constellation, and for all satellites, based on the NANU information are shown in the following table. Note that for continuity and availability, the baseline constellation is affected if at least one of the satellites in an expanded slot is healthy, i.e. an outage on one of the satellites in an expanded slot still affects the statistics for the baseline constellation.

Table 4-5: Summary of NANU Statistics for Monitoring Period

	Q4 2022
Hrs	2208
total forecast downtime (all)	326.50
total forecast downtime (baseline)	302.50
total actual scheduled downtime (all)	134.35
total actual scheduled downtime (baseline)	127.93
Scheduled satellite outage events (all)	27
Scheduled satellite outage events (baseline)	26
Unscheduled satellite outage events (all)	1
Unscheduled satellite outage events (baseline)	1
Total actual unscheduled downtime (all)	1.82
Total actual unscheduled downtime (baseline)	1.82
Total actual downtime (all)	136.17
Total actual downtime (baseline)	129.75
Availability (all)	99.801
Availability (baseline)	99.755
Continuity (baseline)	99.996

5. CONCLUSIONS

The following table summarises the measured performance against the specification.

Table 5-1: Summary of Performance

Criteria	Specifications	Measured Performance	Passed
SPS SIS Accuracy	The User Range Error (URE) ≤7 m 95% for any satellite	All but one SV < 7m	No. Although seems to be due to higher than usual ionospheric residuals
	The User Range Error (URE) ≤2 m 95% for all satellites	4m	No. Although due to higher than usual ionospheric residuals
SPS SIS rms	≤3.6 m	All days <2.5m	Yes.
SPS SIS Integrity	The SIS Integrity $\leq 1\text{x}10^{-5}$ Probability Over Any Hour (<0.7 events per quarter)	No events	Yes Several events are detected but they appear to be local multipath rather than SIS events
SPS SIS Continuity	≥ 0.9998 Probability Over Any Hour	99.996% (1 outage on baseline)	Yes
SPS SIS Availability	SPS SIS Per-Slot Availability • ≥ 0.957 SPS SIS Constellation Availability • ≥ 0.98 Probability that at least 21 Slots out of the 24 Slots will be healthy • ≥ 0.99999 Probability that at least 20 Slots out of the 24 Slots will be healthy • ≥ 0.95 Probability that the Constellation will have at least 24 Operational Satellites	1) 99.75% per-Slot Availability 2) 100% Constellation Availability 3) 100% probability that the number of operational satellites is larger than 24.	Yes
PDOP Availability	• ≥ 98% global PDOP of 6 or less • ≥ 88% worst site PDOP of 6 or less	>99.8% availability on all days	Yes

Criteria	Specifications	Measured Performance	Passed
SPS Position Service Availability	• ≥ 99% Horizontal Service Availability average location • ≥ 90%Horizontal Service Availability worst-case location • ≥ 99% Vertical Service Availability average location • ≥ 90% Vertical Service Availability worst-case location	100% availability on all days	Yes
Positioning Accuracy	• ≤ 8 meters 95% All-in-View Global Average Horizontal Error (SIS Only) • ≤ 15 meters 95% All-in-View worst site Horizontal Error (SIS Only) • ≤ 13 meters 95% All-in-View Global Average Vertical Error (SIS Only) • ≤ 33 meters 95% All-in-View worst site Vertical Error (SIS Only)	1) <4 metres 95% Horizontal Error at the site 2) <10 metres 95% Vertical Error at the site	Yes

From the table it can be seen that the measured performance is within the required values for almost all requirements. The exception is the SIS accuracy, which is because the processing results still include contributions such as ionospheric residual errors which appear larger than usual for most of December.

ANNEX A. ANALYSIS OF HIGH SIS ERRORS

As seen in section 3.2, the analysis of SIS accuracy showed some satellites with large 95% SIS accuracy and one satellite where the threshold of 7m was exceeded. This could indicate a failure of the SIS accuracy requirements.

In addition, the daily rms SIS accuracy and the vertical positioning error (see section 3.8) show some increase in errors after 4th December, which suggests this period has higher than expected errors.

It is noted that the analysis of the errors uses GPS L1 measurements and are affected by propagation errors as well as Signal In Space errors, whereas the performance requirements in the specification consider only SIS errors. Therefore before raising an issue it is necessary to perform some further analysis to determine the likely cause of the errors.

Firstly, we look in more detail at the errors to see if there are particular events or a general period where errors are degraded. As noted from the position error plots, there is a general increase in error after 4th December. If we therefore assess the SIS accuracy before this period and compare it with the figures for the whole period then we can see if that has an effect. The following figures show the 95% SIS accuracy for the whole period (left) and for the period up until 4th December (right). It can clearly be seen that the SIS accuracy is much improved if we consider the short period, indicating that the issue is in the period after 4th December.

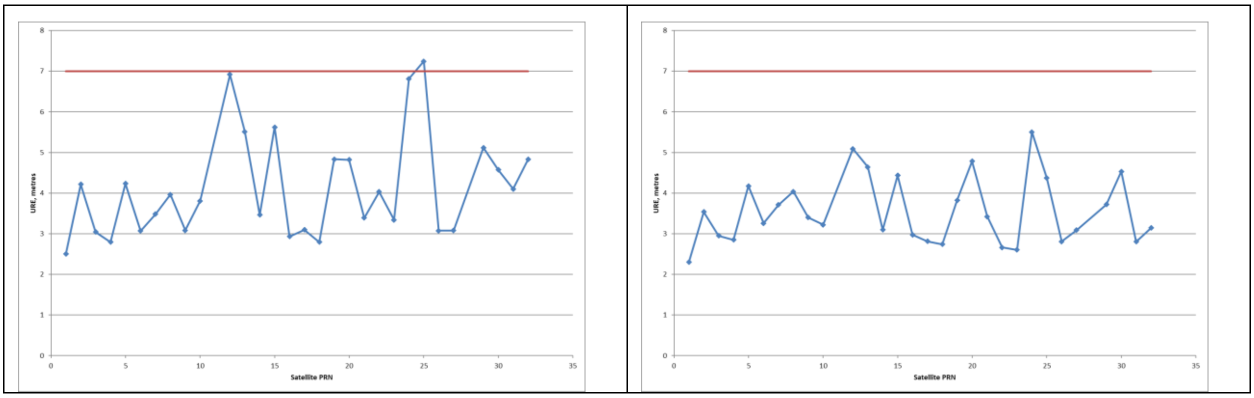

Figure 5-1: Constellation URE (95%) for Reporting Period (left) and Period up until 4th December (right)

As was seen in section 3.8, the vertical error was a bit larger than usual in December for GPS L1 processing. By generating a GPS dual frequency (L1/L2) solution we can compare the errors to see if there is still a problem or if the dual-frequency combination removes the larger errors. The following plot shows the vertical positioning errors for December for L1/L2 solution.

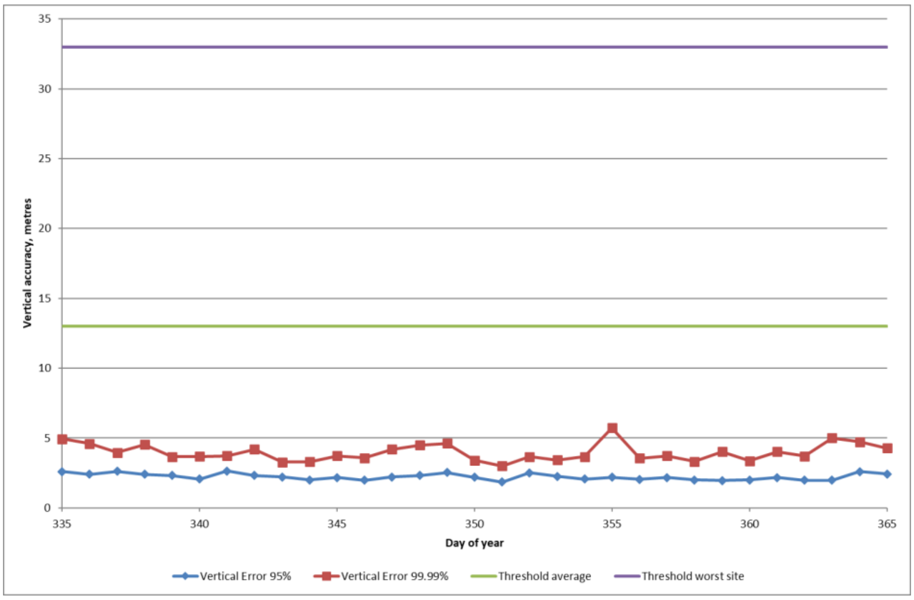

Figure 5-2: Daily Vertical Accuracy Values for December for GPS L1/L2 solution at MLG1

The December values for GPS L1 are also shown for comparison.

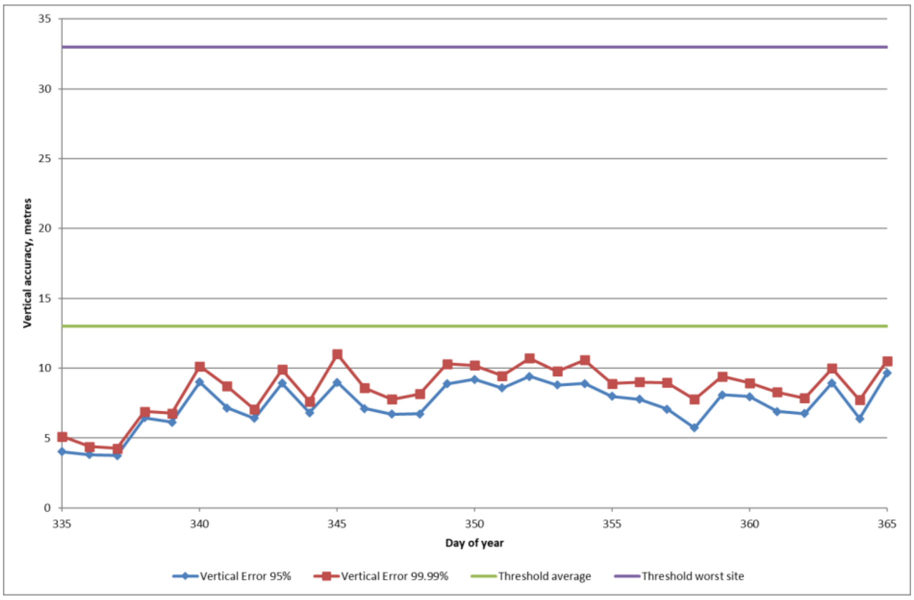

Figure 5-3: Daily Vertical Accuracy Values for December for GPS L1 solution at MLG1

It can be seen that the errors are at a similar level at the start if December but after 4th they are noticeably larger for GPS L1. This strongly suggests high residual ionospheric errors because those are removed through the dual frequency ionospheric free combination, whereas if the problem were a satellite SIS issue (e.g. poor clock) then it would affect both L1 and L1/L2 solutions. Whether this is due to particularly active ionospheric activity or simply poor broadcast ionospheric model parameters is unclear at this stage. Nevertheless, it does confirm that the apparent degraded SIS accuracy performance is due to ionosphere rather than SIS errors and so does not constitute a failure of the SIS accuracy per satellite requirement.

END OF DOCUMENT