GLOBAL POSITIONING SYSTEM (GPS) PERFORMANCE

QUARTERLY REPORT 1 (JANUARY TO MARCH 2024)

Prepared by: Lee Banfield

Approved by: M Pattinson

Authorized by: M Pattinson

Code: GMV_CAA-GPS-SPS-Q1-24

Version: 1.0

Date: 18/04/24

Internal code: GMV 22432/24 V1/24

DOCUMENT STATUS SHEET

Version	Date	Pages	Changes
1.0	18/04/2024	34	First version delivered to CAA

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 January to March 2024. 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 and geomagnetic activity. The performance is analysed using raw data recorded at the GMV Harwell site HARW.

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;
- **Annex A** provides the geomagnetic activity data;
- **Annex B** contains some analysis of the days in March with higher than usual errors.

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]	THE PROVISION OF MONITORING AND ANALYSIS OF GPS SIGNALS IN SPACE –	CONTRACT NO. 1762 (AMENDMENT NO. 12)	-	21/02/24
[AD.2]				
[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	5^{th} Edition	Apr 2020
[RD.2]	Global Positioning System (GPS) Civil Monitoring Performance Specification	DOT-VNTSC-FAA-09-08	-	April 30^{th} 2009
[RD.3]	Reference Set of Parameters for RAIM Availability Simulations', EUROCAE WG-62	-	-	8-9 July 2003
[RD.4]	The International GNSS Service in a changing landscape of Global Navigation Satellite Systems	Journal of Geodesy 83: 191-198		2009

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
CAA	Civil Aviation Authority
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HDOP	Horizontal Dilution Of Precision
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
	• $\leq 1x10^{-5}$ 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:** • $\leq 1x10^{-5}$ 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:** • $\leq 1x10^{-5}$ Fraction of Time when the SPS SIS Instantaneous URE Exceeds the NTE Tolerance Without a Timely Alert (Psat) ***[New specification – did not appear previously]*** • $\leq 1x10^{-8}$ 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 continuously operating receivers, installed by GMV at their Nottingham and Harwell offices, and that provide a log of 1Hz GNSS measurement data. These are shown in the map below.

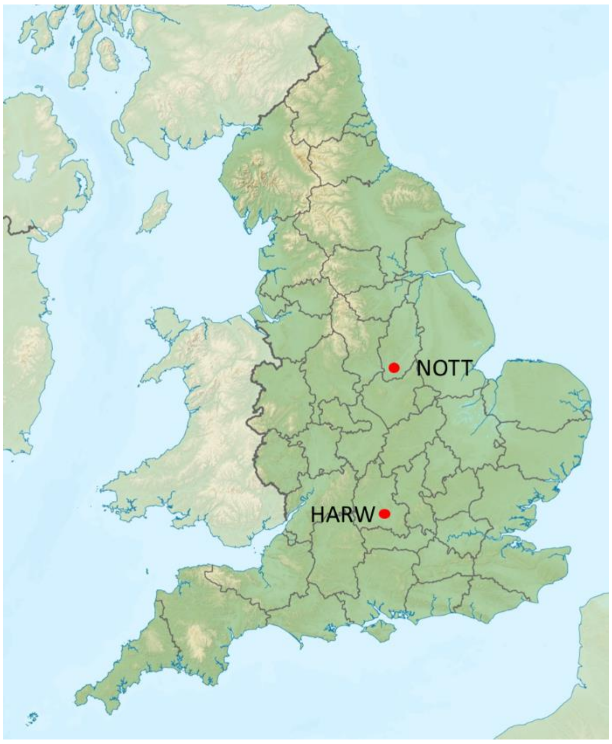

Figure 2-1: Location of GMV Monitoring Receivers

As an alternative, data from the EUREF permanent GPS network can be used (as shown in the next figure). The EUREF receivers provide high rate (1Hz), multi-constellation, multi-frequency GNSS measurements. The data files are accessed via ftp and can be downloaded at GMV NSL before processing with GISMO SW. The daily navigation message files are also downloaded from the IGS ftp site and used to provide the navigation data [RD.4].

Figure 2-2: Location of EUREF Sites
(http://www.epncb.oma.be/_networkdata/stationmaps.php)

In this quarter, data from the GMV Harwell site (HARW) is used for the entire 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

Elevation, degrees	Error, metres
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 table shows the satellite PRN in each slot for the baseline constellation for the period January to March 2024[1].

Table 3-1: Baseline constellation in the Period 1 January to 31 March 2024

Slot	A1	A2A/A2F	A3	A4	B1A/B1F	B2	B3	B4	C1	C2	C3	C4A/C4F
PRN	24	31/28	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

It is noted that during a previous period, SVN63 (PRN1) from slot D2A had an issue on 10th July 2023 and was set unhealthy, and then was decommissioned on 10th August. Another satellite (SVN44) was re-activated to broadcast PRN22 from 18th August but there is no information available on the plane and slot in which that satellite is located.

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 January to March 2024 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 March 2023 and before that on 1st June 2022.

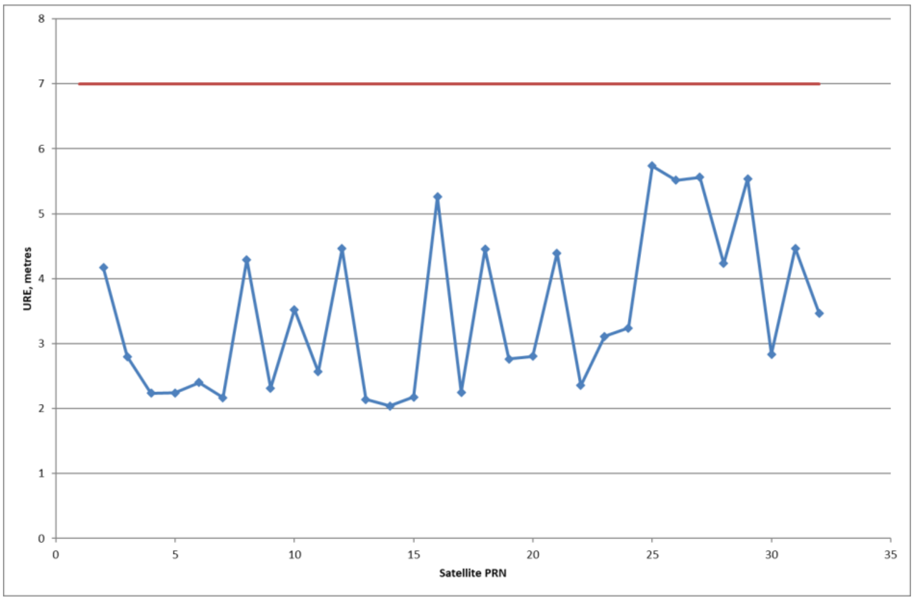

Figure 3-1: Constellation URE (95%) for Reporting Period

It can be seen that the URE (95%) for all satellites is below the 7m threshold.

The daily constellation RMS URE results in the period January to March 2024 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.

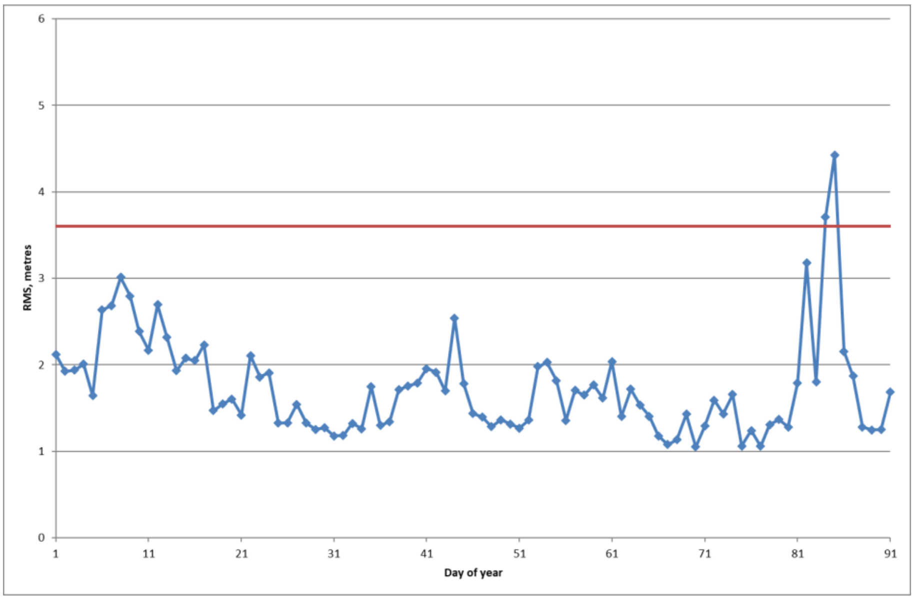

Figure 3-2: Constellation RMS URE for Reporting Period

It can be seen that the RMS values are below the threshold (3.6 metres) on almost all days, although they are higher during a couple of days in March due to high ionospheric activity (as discussed further in Annex B).

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 January to March 2024 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	-	-	-	-	-	-
2	1.65	2.20	1.46	4.17	9.97	2217032
3	0.13	1.44	1.44	2.80	7.86	2363758
4	0.00	1.09	1.09	2.24	6.82	2700419
5	0.41	1.17	1.10	2.24	7.93	2714635
6	0.02	1.27	1.27	2.40	7.07	2786994
7	0.55	1.21	1.07	2.17	6.50	2804253
8	1.13	2.35	2.06	4.29	11.24	2280677
9	0.51	1.24	1.13	2.31	8.11	2422140
10	0.65	1.87	1.75	3.52	10.83	2583270
11	-0.26	1.37	1.35	2.57	7.44	2807827
12	0.70	2.05	1.93	4.46	9.09	2277657
13	0.46	1.09	0.98	2.14	6.58	2125400
14	0.35	1.08	1.02	2.04	8.45	2810448
15	0.02	1.08	1.09	2.18	8.20	2439326
16	1.40	2.61	2.21	5.26	12.66	2573608
17	0.28	1.16	1.13	2.25	5.53	2863122
18	0.53	2.18	2.12	4.45	11.32	2754368
19	0.93	1.45	1.11	2.76	5.57	2856896
20	0.94	1.56	1.25	2.81	6.63	2649529
21	1.94	2.46	1.51	4.40	10.91	2223493
22	0.75	1.25	1.01	2.36	7.01	2787507
23	0.09	1.64	1.64	3.11	8.77	2863324
24	0.59	1.58	1.47	3.24	7.87	2095891
25	1.62	2.71	2.17	5.73	10.36	2126266
26	1.38	2.79	2.43	5.52	12.29	2427933
27	1.85	2.88	2.21	5.56	11.68	1356657
28	0.05	2.20	2.20	4.23	9.73	2734655
29	1.04	2.54	2.33	5.54	10.51	2579230
30	1.11	1.59	1.14	2.84	8.99	2592044
31	0.63	2.17	2.08	4.47	9.65	2773686
32	0.38	1.76	1.72	3.47	7.63	2885524

PRN	Range Error (mean)	Range Error (RMS)	1-sigma	Range Error (95%)	Range Error (max)	Number of Samples
Total	0.66	1.65	1.51	3.63	12.66	78477569

Overall, the measured SIS accuracy for any satellite is below the threshold values throughout the monitoring period for all satellites.

The measured accuracy for all satellites combined is above the threshold of 2m, which is likely due to 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 1×10^{-5}/hr probability for misleading information, 91-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 2 days where this condition is met, which are 24th and 25th March. These are also days where we see higher SIS URE errors and larger vertical errors than usual. If we reprocess with dual frequency (L1/L2) then there are no SIS URE errors on those days, which suggests these were due to higher than usual ionospheric errors.

As the high errors that were measured appear to be due to effect other than SIS errors, therefore the SIS integrity requirement is passed in this period.

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 (which continued from Q4 2023), lasting for a total of 786.87 hrs in this quarter. Therefore this gives a continuity figure of 98.499% in this period, which does not meet the requirement of 99.98% in this period.

For the previous rolling year, there have been 7 unscheduled outages on the baseline constellation lasting for 2144.57 hrs in total. This gives a continuity value for the year of 98.983%, which does not meet the performance standard.

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 1113.68 hours. This is equivalent to an average of 0.97875 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.

For the previous rolling year, the total period in which satellites from the baseline 24-satellite constellation did not broadcast a healthy SIS was 2557.45 hours. This is equivalent to an average of 0.98787 over all slots in the 24-slot constellation and satisfies SPS SIS Per-slot Availability (≥ 0.957).

The minimum number of the baseline constellation satellites broadcasting healthy SPS SIS was 22, greater than the specifications of 20 and 21, and the minimum number of operational satellites broadcasting healthy messages was 29. This means that all constellation availability requirements from the Performance Standard are met for the previous year.

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 January to March 2024.

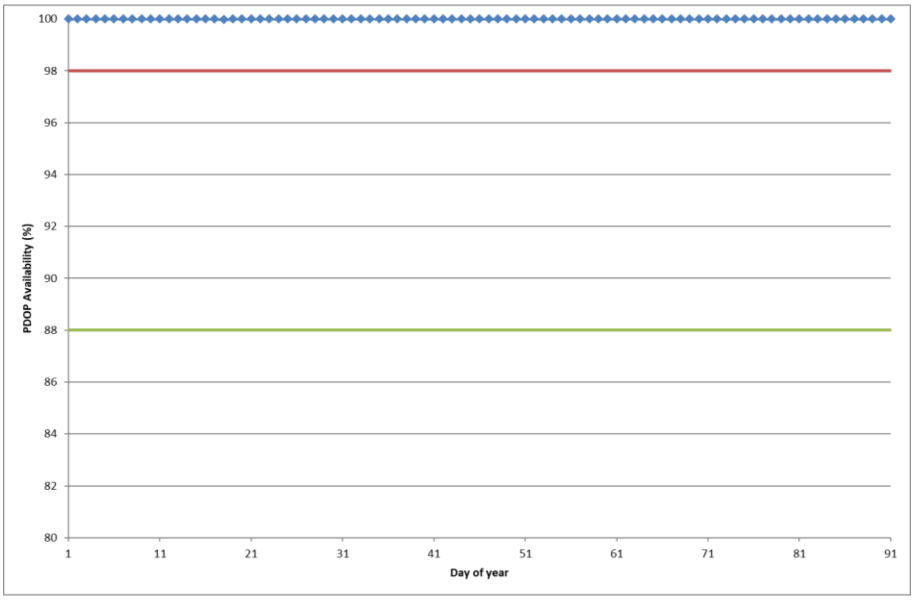

Figure 3-3: Daily PDOP Availability in the Reporting Period

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.

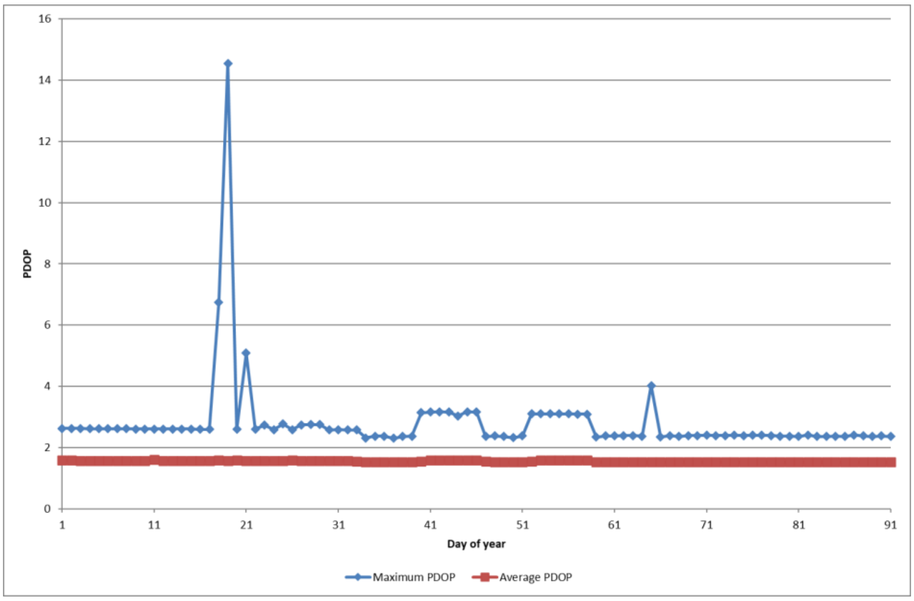

Figure 3-4: Daily Maximum PDOP Value in the Reporting Period

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 almost all days the maximum PDOP is well below the threshold of 6, but there are 2 days (18th and 19th January) when the maximum PDOP is very large. However, on these days there appears to be local interference at the sites, which cases some issues with satellite tracking for short periods, and during those times the PDOP is degraded.

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 January to March 2024 are shown in the following figures.

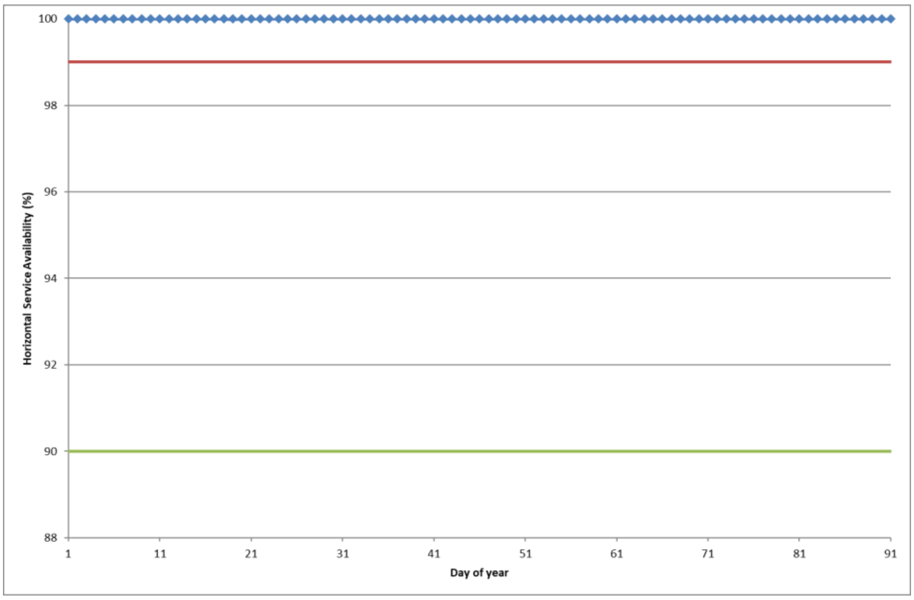

Figure 3-5: Daily Horizontal Service Availability Values for Reporting Period

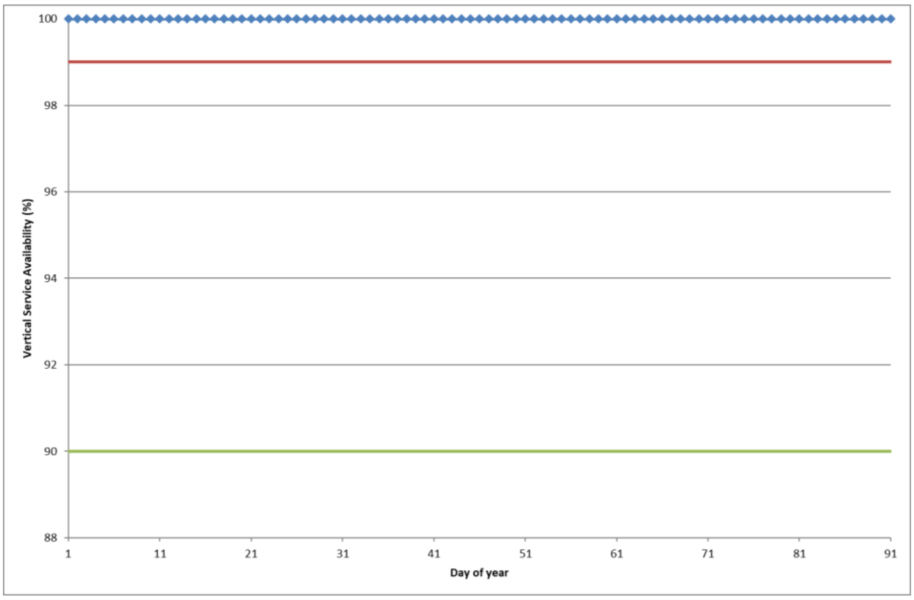

Figure 3-6: Daily Vertical Service Availability Values for Reporting Period

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 January to March 2024 are shown in the following figures.

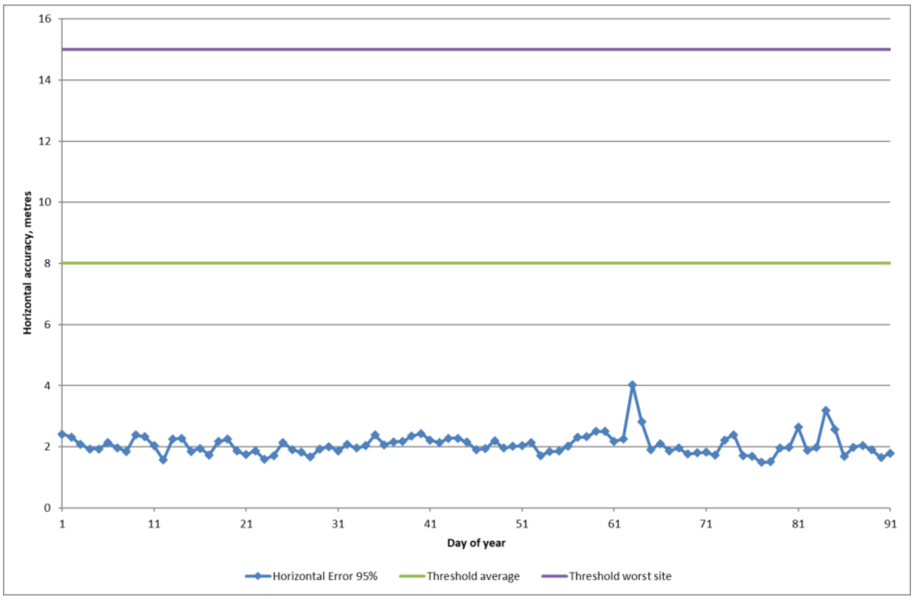

Figure 3-7: Daily Horizontal Position Accuracy (95%) for Reporting Period

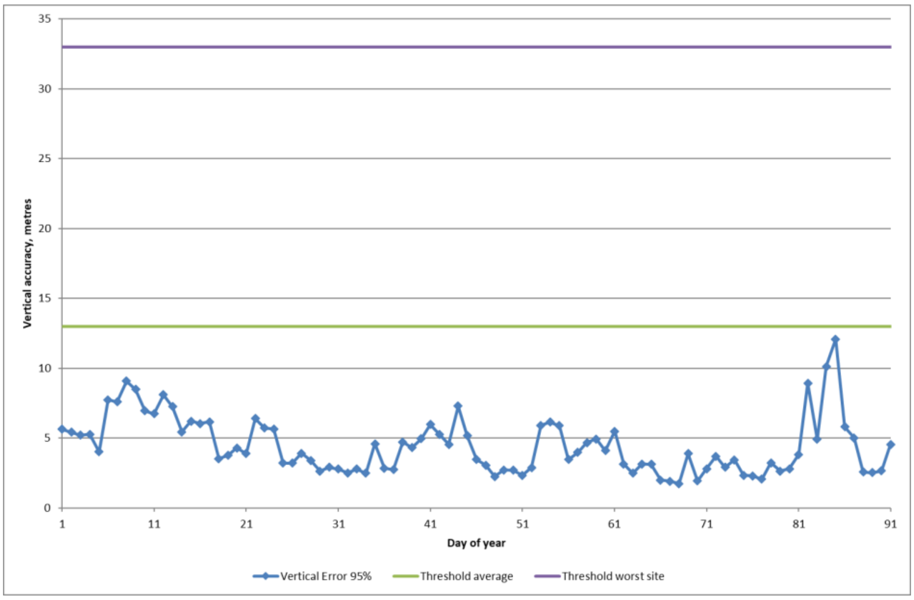

Figure 3-8: Daily Vertical Position Accuracy (95%) for Reporting Period

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 below the thresholds of 13m (global average) and 33m (worst site), although it is noted there are a few days towards the end of the period when vertical errors are larger than usual and are close to the threshold.

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

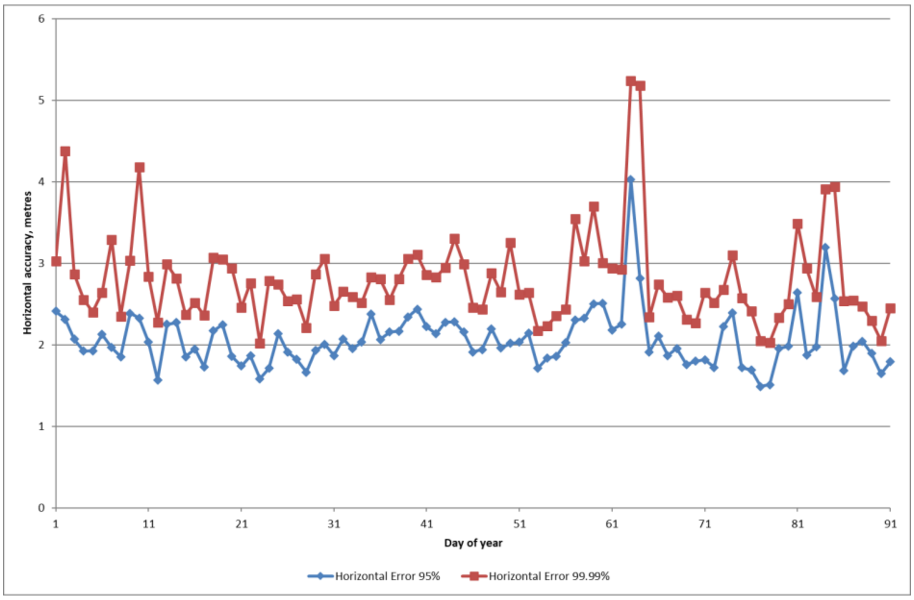

Figure 3-9: Daily Horizontal Position Accuracy (99.99%) for Reporting Period

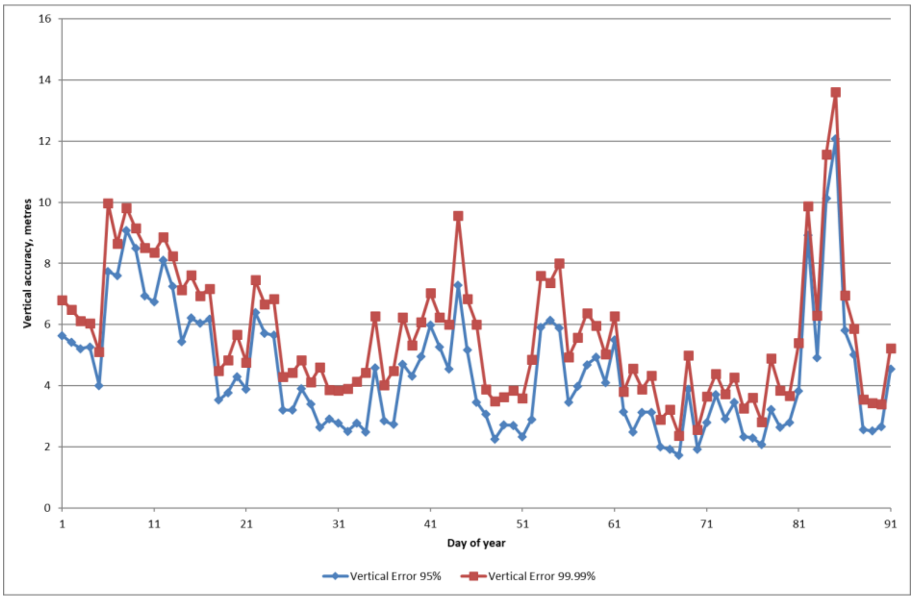

Figure 3-10: Daily Vertical Position Accuracy (99.99%) for Reporting Period

It can be seen that on most days 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
2023075	3	FCSTDV	5	745	5	1945	12	E1
2024002	24	FCSTDV	11	1130	11	2330	12	A1
2024004	5	FCSTDV	26	200	26	1400	12	E3A
2024006	2	FCSTDV	40	230	41	230	24	D5
2024008	10	FCSTMX	40	1600	50	1600	240	E2
2024010	8	FCSTMX	52	2030	62	2030	240	C3
2024013	4	FCSTDV	68	750	68	1950	12	F4
2024016	29	FCSTDV	80	1500	81	300	12	C1

Table 4-2: Summary of Actual Scheduled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2024001	3	FCSTSUMM	5	748	5	1231	4.71667	2023075
2024003	24	FCSTSUMM	11	1148	11	1637	4.81667	2024002
2024005	5	FCSTSUMM	26	218	26	737	5.31667	2024004
2024009	2	FCSTSUMM	40	231	40	833	6.03333	2024006
2024011	10	FCSTSUMM	40	1642	47	821	159.65000	2024008
2024012	8	FCSTSUMM	52	2059	58	2211	145.20000	2024010
2024015	4	FCSTSUMM	68	750	68	1348	5.96667	2024013
2024017	29	FCSTSUMM	80	1936	80	2045	1.15000	2024016

Table 4-3: Summary of Cancelled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Ref
-	-	-	-	-	-	-	-

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

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2023076	27	UNUSUFN	364	1107	NA	NA	NA	C2
2024007	27	UNUSABLE	1	0	33	1852	786.8666667	2023076

Note that the unscheduled outage started in Q4 2023, but only the portion that affected Q1 2024 is included in the figures for this quarter.

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

	Q1 2024
Hrs	2184
total forecast downtime (all)	564.00
total forecast downtime (baseline)	540.00
total actual scheduled downtime (all)	332.85
total actual scheduled downtime (baseline)	326.82
Scheduled satellite outage events (all)	8
Scheduled satellite outage events (baseline)	7
Unscheduled satellite outage events (all)	1
Unscheduled satellite outage events (baseline)	1
Total actual unscheduled downtime (all)	786.87
Total actual unscheduled downtime (baseline)	786.87
Total actual downtime (all)	1119.72
Total actual downtime (baseline)	1113.68
Availability (all)	98.346
Availability (baseline)	97.875
Continuity (baseline)	98.499

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 SV < 7m	Yes
	The User Range Error (URE) ≤2 m 95% for all satellites	<4m	No. Although likely due to ionospheric residuals
SPS SIS rms	≤3.6 m	Most days <3.6m	No. Although seems to be due to higher than usual ionospheric residuals
SPS SIS Integrity	The SIS Integrity ≤1×10^{-5} Probability Over Any Hour (<0.7 events per quarter)	No SIS events	Yes Some events are detected but they appear to be high iono rather than SIS events
SPS SIS Continuity	≥ 0.9998 Probability Over Any Hour	98.499% (one unscheduled outage on baseline) 98.983% for rolling year	No for monitoring period. No for rolling year.
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) 97.9% per-Slot Availability 2) 100% Constellation Availability 3) 100% probability that the number of operational satellites is larger than 24.	Yes, for both monitoring period and rolling year.
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) <13 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 most requirements. The exceptions are the SIS accuracy, which is because the processing results still include contributions such as ionospheric residual errors which appear larger than usual for two days in March, and the SIS continuity requirement, due to a long unscheduled outage.

ANNEX A. GEOMAGNETIC DATA

The solar activity during a particular period can be determined using the K index data provided by the British Geological Survey (BGS) in the UK. This data is available from http://www.geomag.bgs.ac.uk/data_service/data/magnetic_indices/k_indices.html. The K index at each observatory summarises the geomagnetic activity by assigning an index value (in the range 0 – 9) to each 3-hr time interval. The index values are determined from the maximum range in H or D with allowance made for the normal (undisturbed) diurnal variation. The conversion from range to index value is made using a quasi-logarithmic scale, with the scale values dependent on the geomagnetic latitude of the observatory. In general, the higher the K index the more active the Earth's magnetic field. K-index values of 5 of higher indicate geomagnetic storm level activity and index values of 7 or higher indicate a severe geomagnetic storm. The geomagnetic activity is important to consider for GPS signals as geomagnetic storms may affect GPS performance, either by increasing the residual ionospheric delay errors in the position solution or by causing problems with tracking the satellite signals. The following figures show the K-index values at 3 sites in the UK during the monitoring period. The figures are reproduced with the permission of the British Geological Survey ©NERC. All rights reserved.

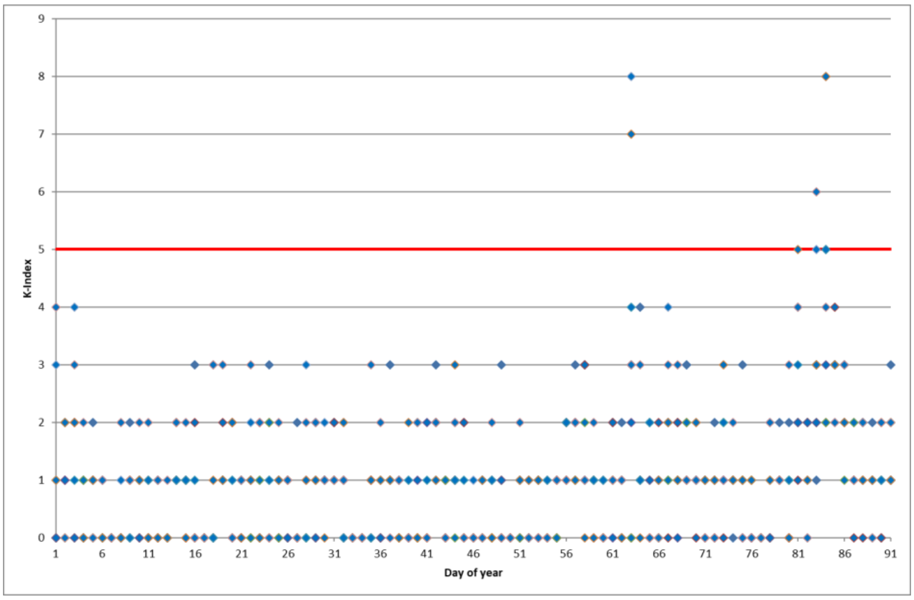

Figure 5-1: K-Index Values at Lerwick during Reporting Period

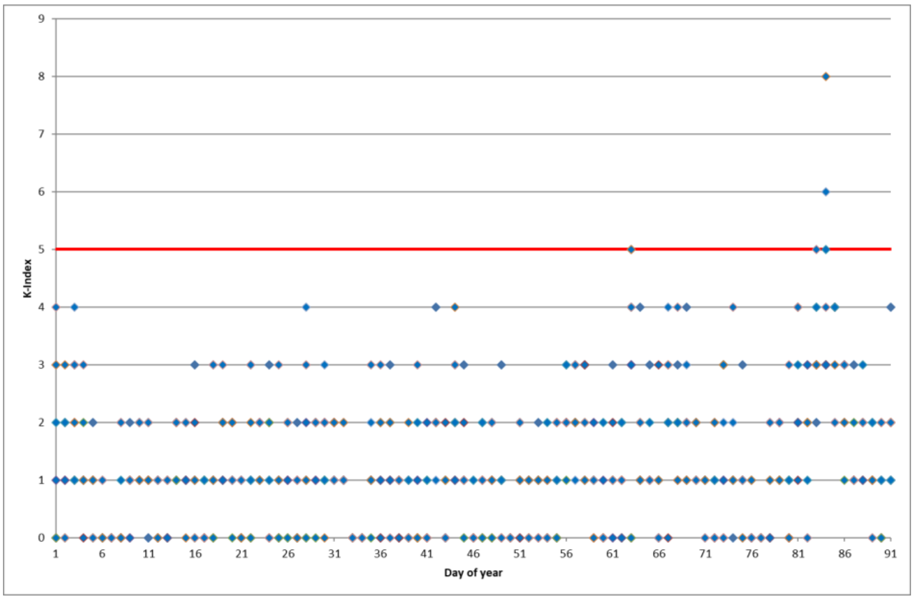

Figure 5-2: K-Index Values at Eskdalemuir during Reporting Period

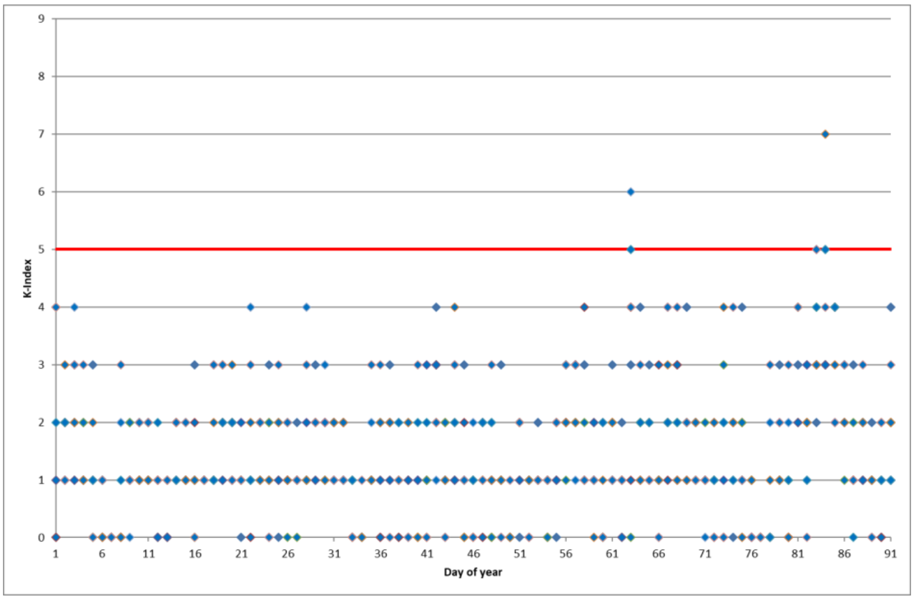

Figure 5-3: K-Index Values at Hartland during Reporting Period

It can be seen that during the monitoring period there are a few occasions where high geomagnetic storm conditions (K index >=7) are observed but most of the period has lower activity.

ANNEX B. ANALYSIS OF HIGH SIS ERRORS

As seen in section 3.2, the daily rms SIS accuracy showed larger than usual errors and even exceeded the threshold on two days. In addition, the vertical positioning errors (see section 3.8) show some larger errors on the same days, 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.

The most likely cause for these sorts of errors, which do not have an associated RAIM fault detection flag raised, are ionospheric residual errors. To test if this is likely to be the case we first look at mean and 95% daily horizontal and vertical errors for the period and compare single frequency and dual-frequency GPS results.

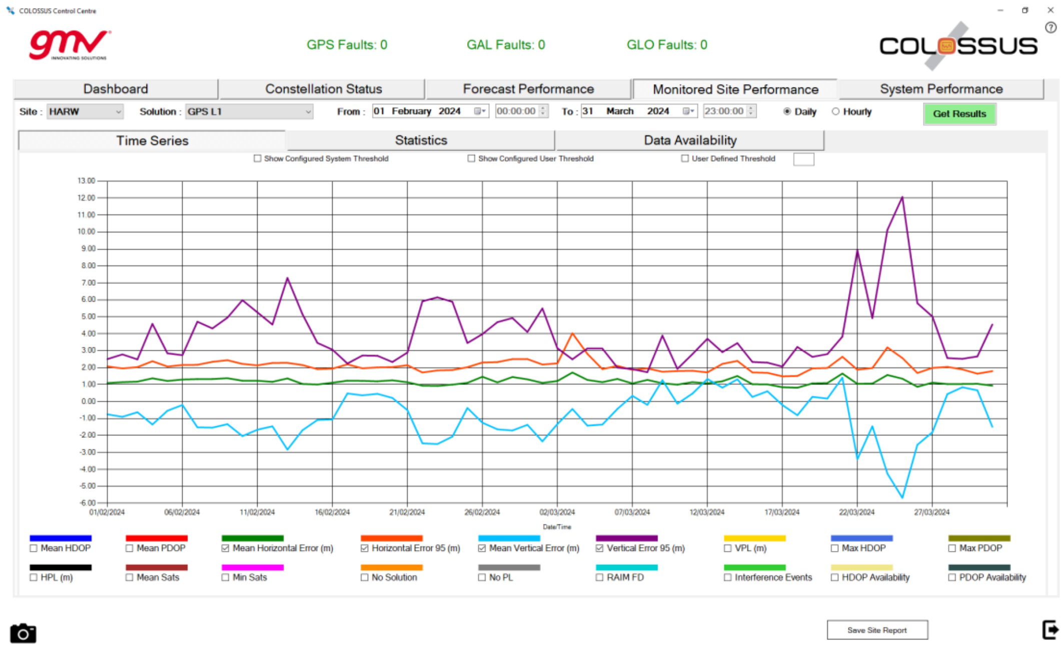

Figure 5-4: Daily Horizontal and Vertical Error Statistics for GPS L1 during Q1 2024

It can be clearly seen that the vertical error statistics are larger at the end of March. The equivalent plot for a dual frequency GPS L1/L2 solution is shown below.

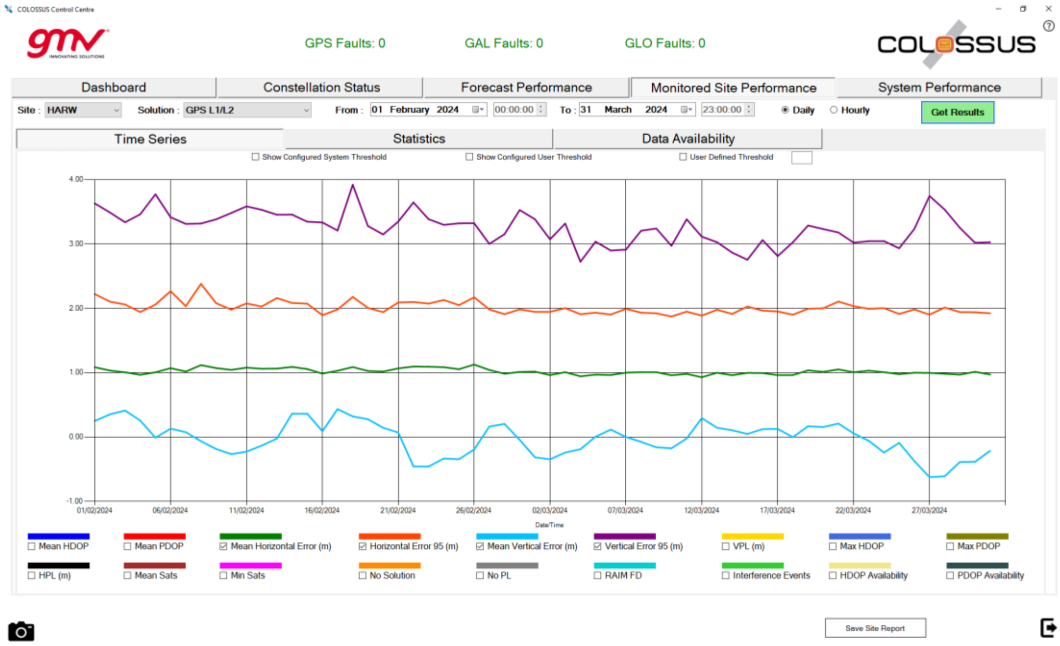

Figure 5-5: Daily Horizontal and Vertical Error Statistics for GPS L1/L2 during Q1 2024

For dual frequency (L1/L2) results, the error statistics are stable throughout the period and at low levels – for both vertical and horizontal errors. This is a strong indication that the higher errors at the end of March are due to increased ionospheric residuals rather than SIS errors, as an error in satellite orbit or clock failure, for example, would affect both single frequency and dual frequency solutions.

Additionally, we also compute the daily rms URE errors for the dual frequency case (equivalent to Figure 3-2).

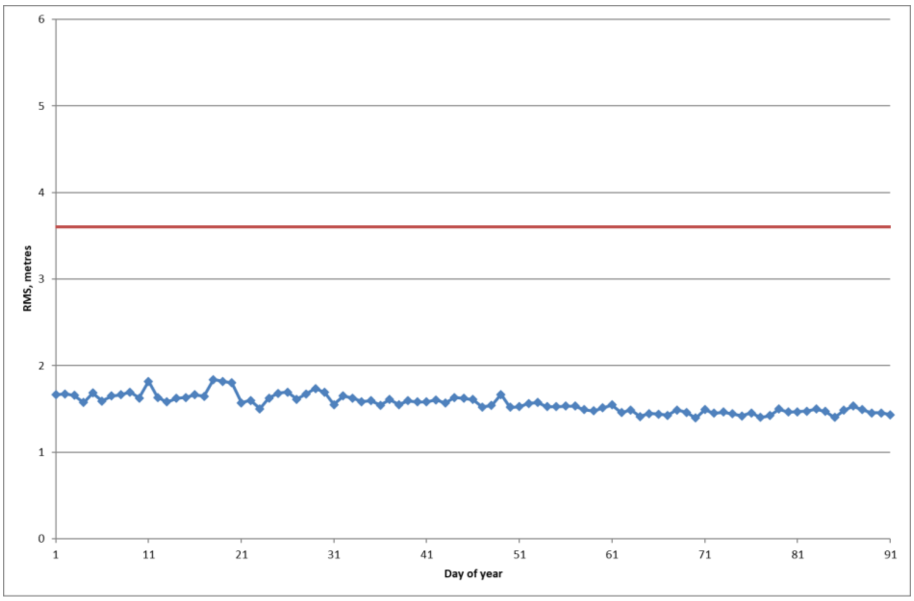

Figure 5-6: Constellation RMS URE (dual frequency) for Reporting Period

It can be seen that the RMS values are below the threshold (3.6 metres) on all days, and the high values towards the end of March are removed. This again indicates that that the higher errors at the end of March are due to increased ionospheric residuals rather than SIS errors and in fact from section ANNEX A. we can see that there are the same days at the end of March with high K-index values, indicating increased ionospheric activity. This would suggest 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 requirement.

END OF DOCUMENT