GLOBAL POSITIONING SYSTEM (GPS) PERFORMANCE

JULY TO SEPTEMBER 2018

QUARTERLY REPORT 3

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1 INTRODUCTION

1.1 Purpose of Document

This document presents the results of the GPS SPS performance assessment for the period of July 2018 to September 2018. 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 Ordnance Survey site LINO, in the central UK.

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;
- **Section 6** (Appendix A) provides the geomagnetic activity data.

1.3 References

1.3.1 Applicable Documents

Ref.	Document title	Document reference	Issue	Date
AD.1	THE PROVISION OF MONITORING AND ANALYSIS OF GPS SIGNALS IN SPACE –	CONTRACT NO. 1762 (AMENDMENT NO. 6)	-	18/12/17

Table 1-1: Applicable Documents

1.3.2 Reference Documents

Ref.	Document title	Document reference	Issue	Date
RD.1	Global Positioning System Standard Positioning Service Performance Standard	GPS SPS	4th Edition	Sept 2008
RD.2	Global Positioning System (GPS) Civil Monitoring Performance Specification	DOT-VNTSC-FAA-09-08	-	April 30th 2009
RD.3	The International GNSS Service in a changing landscape of Global Navigation Satellite Systems	Journal of Geodesy 83: 191-198		2009
RD.4	Reference Set of Parameters for RAIM Availability Simulations', EUROCAE WG-62	-	-	8-9 July 2003

Table 1-2: Reference Documents

1.4 Acronyms

Acronym	Organisation
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
NSL	Nottingham Scientific Ltd

Acronym	Organisation
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

Table 1-3: Acronyms and Abbreviations

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:

Criteria	Specifications
SPS SIS Accuracy	**The User Range Error (URE) for any healthy satellite for Single-Frequency C/A-Code**: • ≤7.8 m 95% Global Average URE during Normal Operations over all age of data (AODs) • ≤6.0m 95% Global Average URE during Normal Operations at Zero AOD • ≤12.8 m 95% Global Average URE during Normal Operations at Any AOD • ≤30 m 99.94% Global Average URE during Normal Operations 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 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:** ≤40 nsec 95% Global Average UTCOE during Normal Operations at Any AOD

Criteria	Specifications
SPS SIS Integrity	**The SIS Integrity for Single-Frequency C/A-Code:** • $\leq 1 \times 10^{-5}$ Probability Over Any Hour of the SPS SIS Instantaneous URE Exceeding the NTE Tolerance Without a Timely Alert during Normal Operations **The UTCOE Integrity for Single-Frequency C/A-Code:** • $\leq 1 \times 10^{-5}$ Probability Over Any Hour of the SPS SIS Instantaneous UTCOE Exceeding the NTE Tolerance Without a Timely Alert during Normal Operations
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
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 • ≥ 99% Vertical Service Availability average location • ≥ 90% Vertical Service Availability worst-case location

Criteria	Specifications
	With 17 m horizontal and 37 m vertical (SIS only) 95% threshold over 24hours
Positioning Accuracy	• ≤ 9 meters 95% All-in-View Global Average Horizontal Error (SIS Only) • ≤ 17 meters 95% All-in-View worst site Horizontal Error (SIS Only) • ≤ 15 meters 95% All-in-View Global Average Vertical Error (SIS Only) • ≤ 37 meters 95% All-in-View worst site Vertical Error (SIS Only) • ≤ 40 nanoseconds time transfer error 95% of time (SIS Only) for Time Transfer Domain Accuracy

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 Ordnance Survey network of active stations in the UK. The Ordnance Survey of Great Britain operates a national GPS network of GPS receiver stations. The network consists of over 50 receivers that provide 24-hour availability of dual frequency GPS and GLONASS data. NSL has access to this data through the Leica SmartNet service, which provides data from the OS network, as well as sites in Ireland and some additional dedicated Leica installations. This means that data from any of the sites in the UK can be used. The network is presented in Figure 2-1.

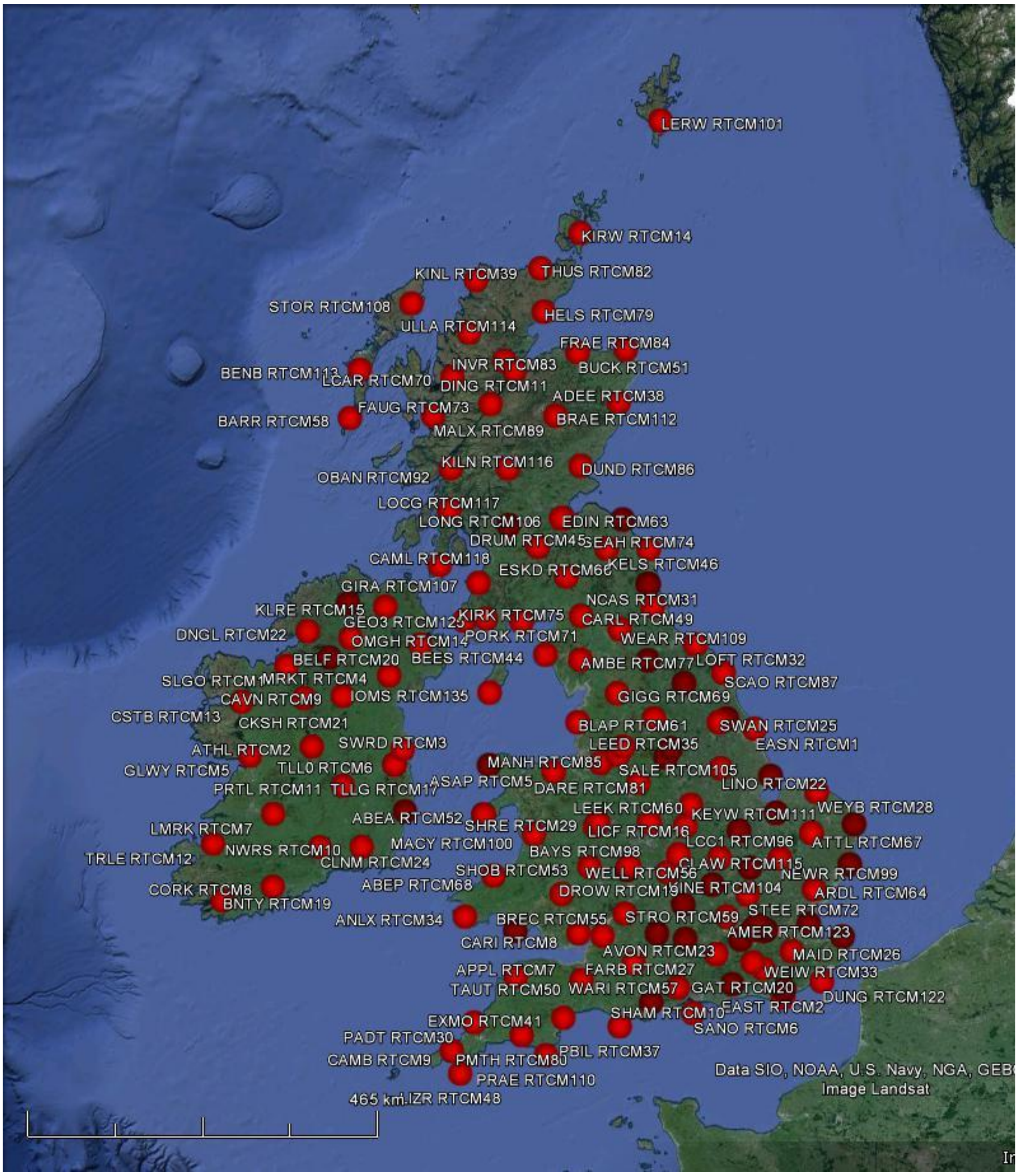

Figure 2-1: Leica SmartNet Network

As only a single site is required for the performance monitoring LINO has been chosen as this is located centrally in the UK and has high data availability with few gaps. Therefore, during this monitoring period, the LINO site is used as the main source of 1Hz data, and hence the performance statistics during this period are based on data from that site.

In case there are problems with the data access from SmartNet, data from the Hert IGS site in the South of the UK can be used. The location of the site is shown in the following Google Earth plot.

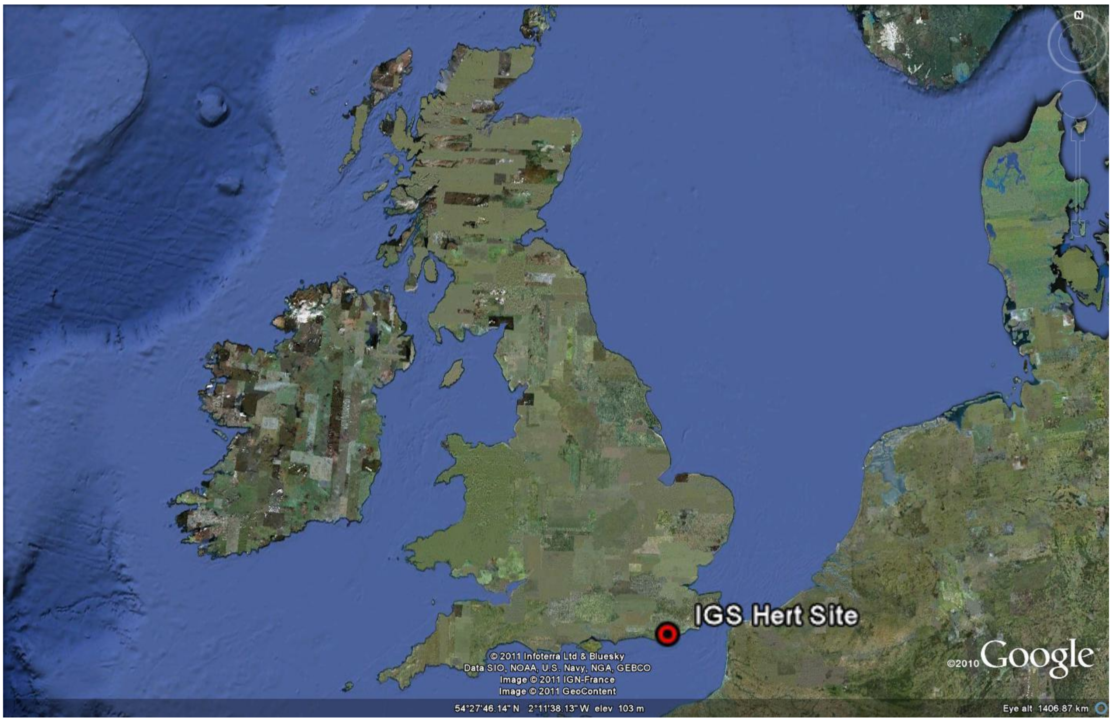

Figure 2-2: Location of IGS Hert Site

The receiver is a Leica GRX1200GGPro geodetic receiver, connected to a LEIAT504GG antenna, which records dual frequency (L1 and L2) GPS and GLONASS measurements at 1Hz rate. The data files are accessed via ftp and are downloaded at NSL before processing with GISMO SW. The daily navigation message files for the Hers receiver at that site are also downloaded from the IGS ftp site and used to provide the navigation data [RD.3].

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 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 17m (95% horizontal accuracy) and 37m (95% vertical accuracy) for 99% of the time are explained a bit more in section B.3.1 of the GPS SPS [RD.1]. The requirement is based on fulfilling a 1-sigma UERE of 4m, HDOP of 2.1 and VDOP of 4.4. 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 < 8.5m (1-sigma);
- Compute daily availability (%) of estimated vertical accuracy < 18.5m (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 are given below [RD.4]:

Elevation, degrees	Error, metres
5	7.48
10	6.64
15	5.92

Elevation, degrees	Error, metres
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. It is important to identify the baseline constellation 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 July to September 2018.

Slot	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
PRN	24	31	30	7	16	25	28	12	29	27	8	17
Slot	D1	D2	D3	D4	E1	E2	E3	E4	F1	F2	F3	F4
PRN	2	1	21	6	3	10	5	20	32	15	9	23

Table 3-1: Baseline constellation in the Reporting Period

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 July to September 2018 are shown in the next figure.

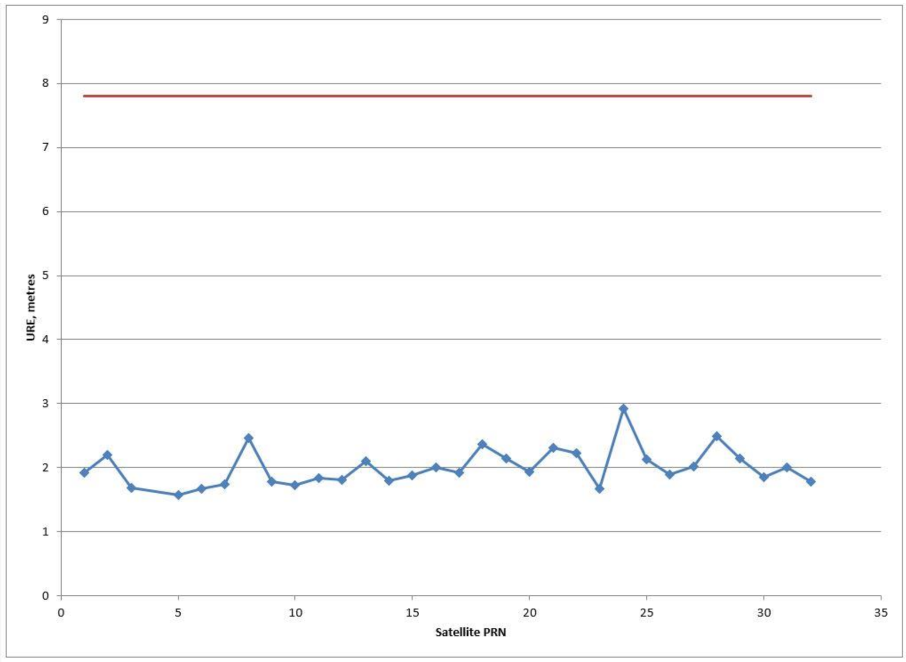

Figure 3-1: Constellation URE (95%) for Reporting Period

It can be seen that the URE (95%) for all satellites is below the 7.8m threshold. The daily constellation RMS URE results in the period July to September 2018 and the 4m threshold are shown in the next figure. Note that ≤ 7.8 m 95% SPS SIS URE performance standard is equivalent to a ≤ 4.0 m RMS SPS SIS URE performance standard [RD.1]. This is also important for the position service availability assessment.

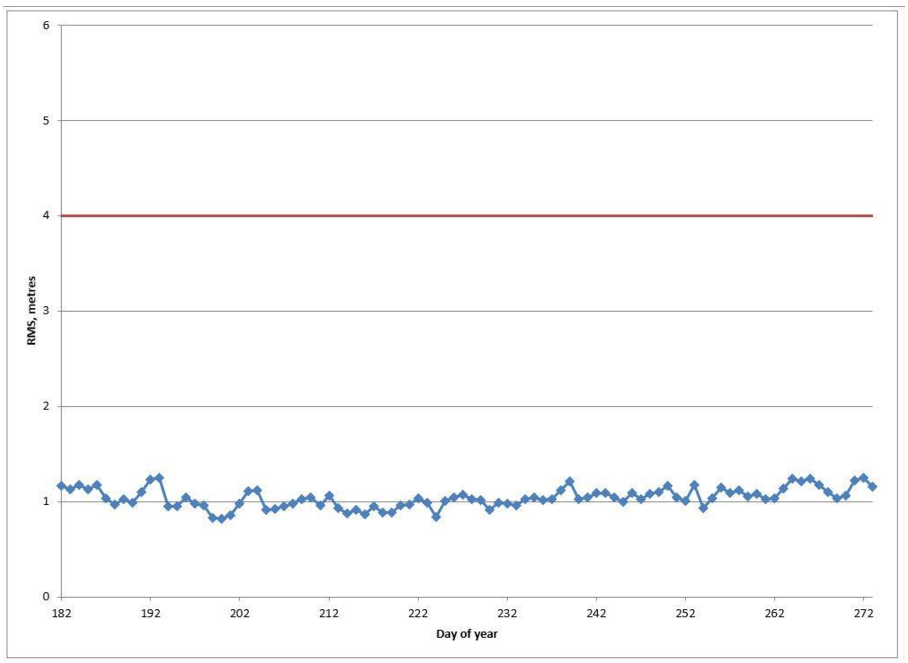

Figure 3-2: Constellation RMS URE for Reporting Period

It can be seen that the RMS values are below the threshold (4 metres) on all days. 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 July to September 2018 are given in the table below.

PRN	Range Error (mean)	Range Error (RMS)	1-sigma	Range Error (95%)	Range Error (max)	Number of Samples
1	-0.25	1.00	0.97	1.91	4.12	2333382
2	0.83	1.19	0.86	2.20	6.59	2890926
3	-0.54	0.90	0.72	1.68	4.06	2313981
5	0.23	0.80	0.76	1.57	3.92	2687149
6	0.15	0.86	0.85	1.66	3.25	2756817
7	0.11	0.90	0.89	1.75	4.13	2790104
8	0.09	1.26	1.25	2.46	6.20	2583714
9	0.36	0.89	0.81	1.78	6.21	2510499
10	-0.32	0.91	0.85	1.73	4.18	2828756
11	-0.26	0.92	0.88	1.84	5.01	2020966
12	0.24	0.94	0.91	1.80	3.61	2498903
13	0.39	1.05	0.98	2.10	4.77	2362965
14	0.30	0.91	0.86	1.80	4.16	2879147
15	0.29	0.97	0.93	1.88	11.79	2537502
16	0.49	1.05	0.93	2.00	4.77	2666784
17	-0.17	0.98	0.96	1.92	19.99	2908958
18	-0.20	1.20	1.18	2.37	5.31	2043821
19	0.94	1.20	0.74	2.14	4.83	2787894
20	0.64	1.03	0.81	1.94	4.45	2825071
21	0.84	1.21	0.86	2.32	4.42	2775531
22	0.95	1.22	0.76	2.22	5.14	2205528
23	-0.23	0.89	0.86	1.66	4.05	2654962
24	0.49	1.47	1.39	2.92	11.44	2095432
25	0.60	1.16	1.00	2.13	5.58	2208176
26	-0.06	0.98	0.98	1.89	4.17	2556391
27	-0.04	0.97	0.97	2.02	4.55	2345530
28	0.34	1.30	1.25	2.49	6.03	2923449
29	0.39	1.09	1.02	2.14	6.50	2613372
30	0.40	0.95	0.86	1.85	4.45	2648685
31	-0.31	1.04	0.99	2.00	4.64	2752968
32	-0.30	0.94	0.89	1.78	18.49	2842886

Table 3-2: Range Error Statistics for Reporting Period

Overall, the measured SIS accuracy is below the threshold values throughout the monitoring period.

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 0.67.

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 no days where this condition is met 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 were no unscheduled outages. Therefore, the continuity in this period was 100%, which meets the requirement of 99.98%.

For the previous rolling year, there have been three unscheduled outages on the baseline constellation lasting for 1088.52 hrs in total. This gives a continuity value for the year of 99.48%, 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 18.70 hours. This is equivalent to an average of 0.9997 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 23, 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 30. 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 broadcast an unhealthy SIS was 1182.93 hours. This is equivalent to an average of 0.995 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, 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 July to September 2018.

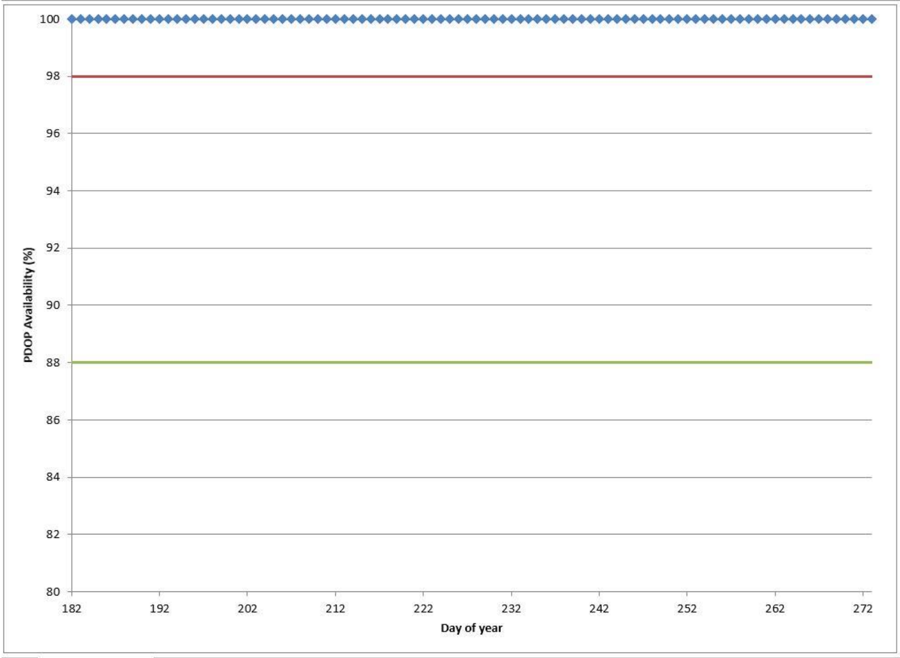

Figure 3-3: Daily PDOP Availability in the Reporting Period

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.

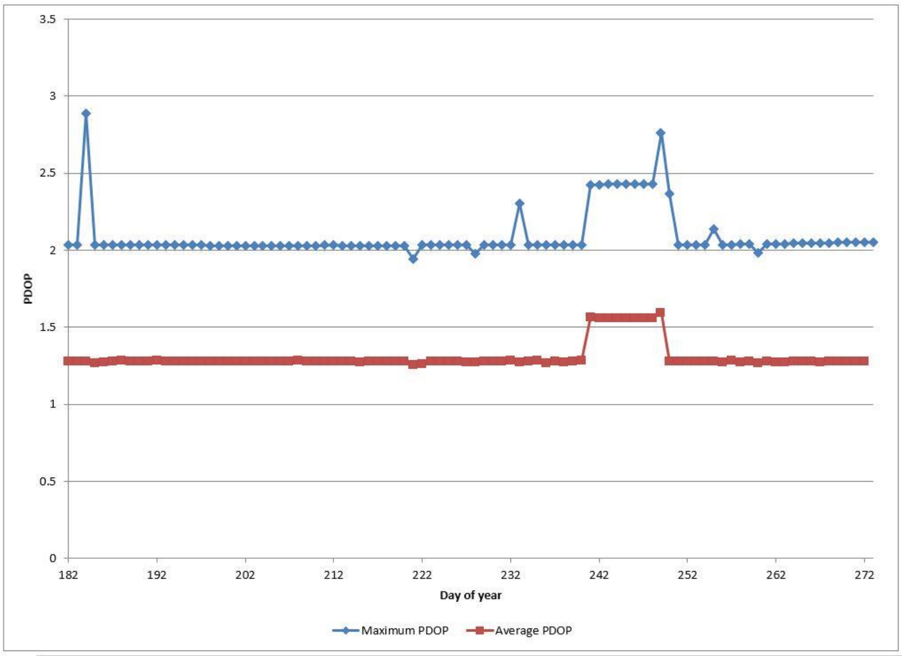

Figure 3-4: Daily Maximum PDOP Value in the Reporting Period

The daily PDOP values PDOP can be used to identify specific days that have different performance from the others. It can be seen is that the maximum PDOP is always below the threshold of 6.

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:

- 17 meters horizontal (SIS only) 95% threshold;
- 37 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 2.2.

The daily horizontal and vertical service availabilities for the period July to September 2018 are shown in the following figures.

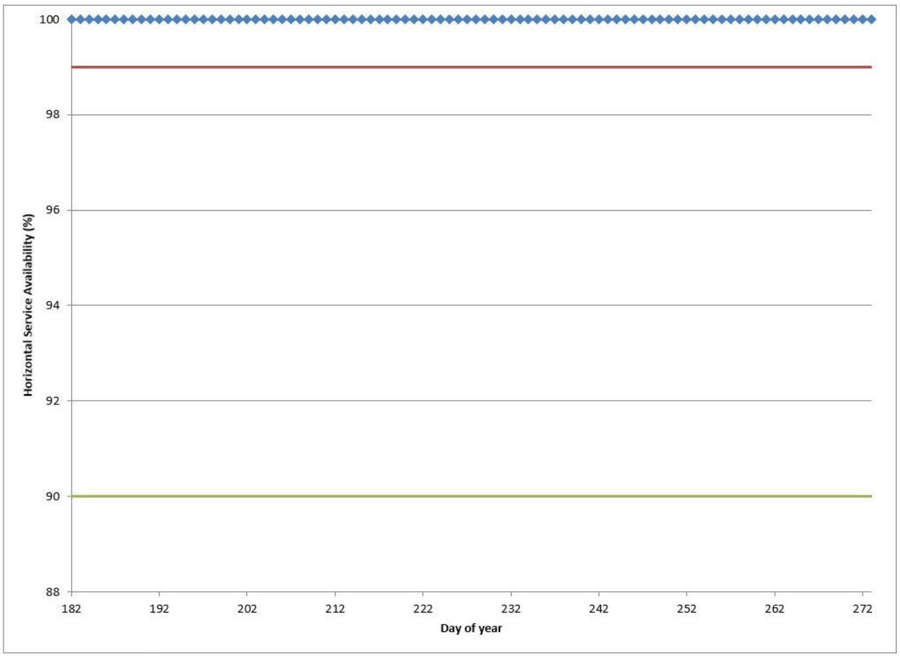

Figure 3-5: Daily Horizontal Service Availability Values for Reporting Period

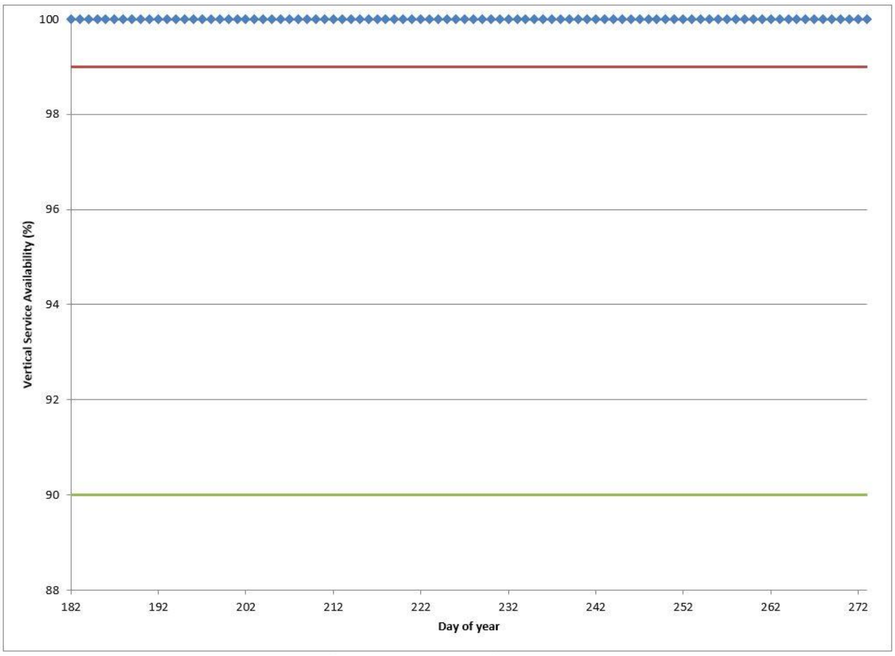

Figure 3-6: Daily Vertical Service Availability Values for Reporting Period

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 July to September 2018 are shown in the following figures.

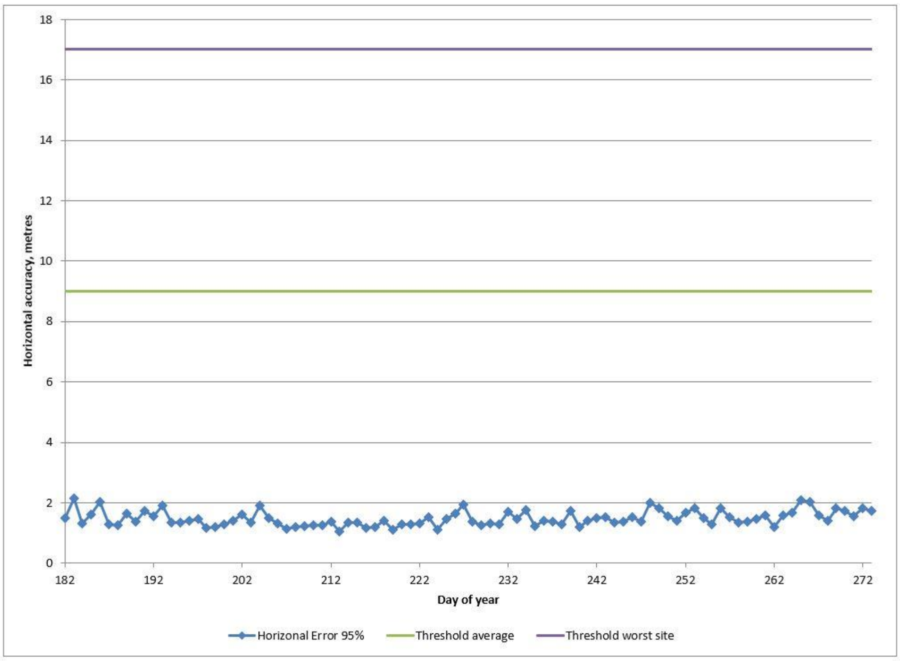

Figure 3-7: Daily Horizontal Position Accuracy (95%) for Reporting Period

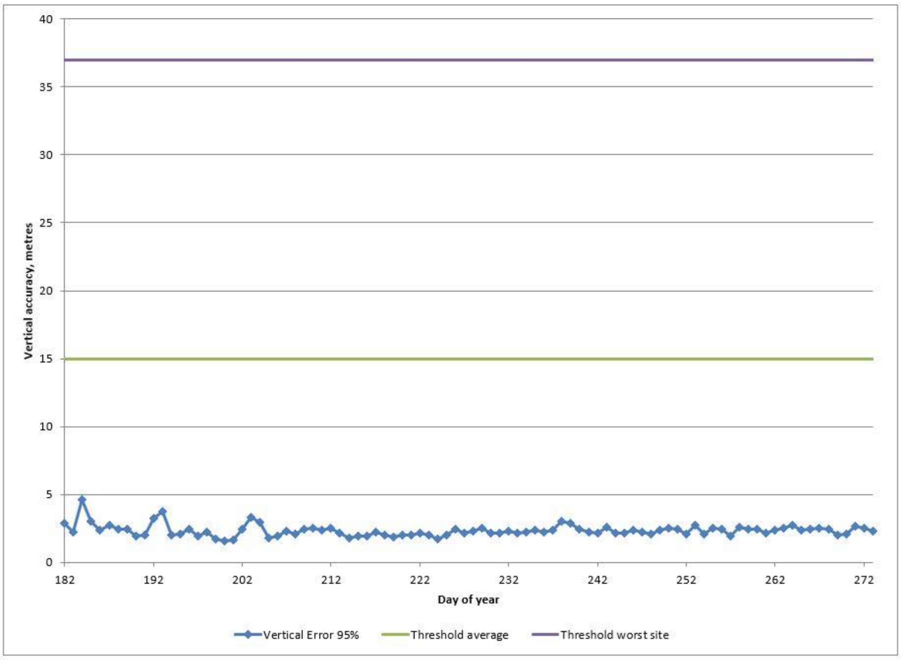

Figure 3-8: Daily Vertical Position Accuracy (95%) for Reporting Period

It can be seen that the daily horizontal accuracy values are all below the thresholds of 9m (global average) and 17m (worst site). The daily vertical accuracy values are also well below the thresholds of 15m (global average) and 37m (worst site). In addition, the daily position accuracy values at the 99.99% level are shown for the same period.

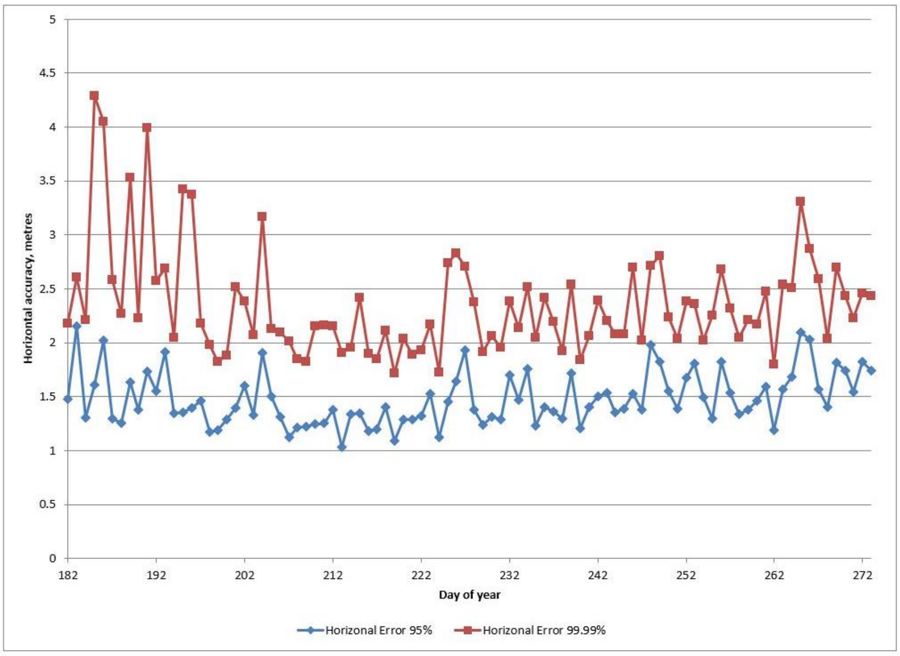

Figure 3-9: Daily Horizontal Position Accuracy (99.99%) for Reporting Period

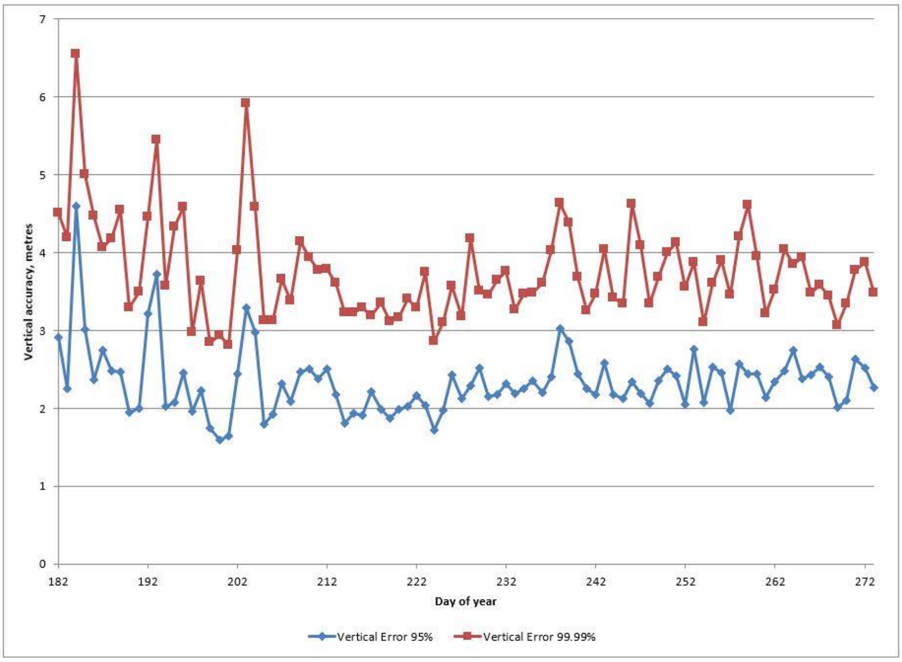

Figure 3-10: Daily Vertical Position Accuracy (99.99%) for Reporting Period

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

NANU information is downloaded from the US Coast Guard Navigation Centre website (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 the baseline constellation are highlighted in green.

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2018031	12	FCSTDV	228	1625	229	425	12	B4
2018033	15	FCSTDV	242	1130	242	2330	12	F2
2018035	2	FCSTDV	249	1455	250	255	12	D1
2018036	15	FCSTDV	254	1105	254	2305	12	F2
2018038	19	FCSTDV	257	810	257	2010	12	C5

Table 4-1: Summary of Forecast Scheduled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2018032	12	FCSTSUMM	228	1721	228	2306	5.75	2018031
2018037	2	FCSTSUMM	249	1521	249	2126	6.083333	2018035
2018039	15	FCSTSUMM	254	1145	254	1837	6.866667	2018036
2018040	19	FCSTSUMM	257	839	257	1406	5.45	2018038

Table 4-2: Summary of Actual Scheduled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Ref
2018034	15	FCSTCANC	242	1130	NA	NA	2018033

Table 4-3: Summary of Cancelled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
-	-	-	-	-	-	-	-	-

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

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.

	Q3 2018
hrs	2208
total forecast downtime (all)	60.00
total forecast downtime (baseline)	48.00
total actual scheduled downtime (all)	24.15
total actual scheduled downtime (baseline)	18.70
Scheduled satellite outage events (all)	4
Scheduled satellite outage events (baseline)	3

Unscheduled satellite outage events (all)	0
Unscheduled satellite outage events (baseline)	0
Total actual unscheduled downtime (all)	0.00
Total actual unscheduled downtime (baseline)	0.00
Total actual downtime (all)	24.15
Total actual downtime (baseline)	18.70
Availability (all)	99.965
Availability (baseline)	99.965
Continuity (baseline)	100.000

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

From the results it can be seen that the forecast downtime was greater than the actual downtime. Also, the actual scheduled downtime periods were within the time period described in the forecast NANUs. From analysis of the broadcast navigation messages it can be seen that all occurrences of unhealthy satellites were linked with NANUs.

There were no unscheduled outages in this period.

5 CONCLUSIONS

The following table summarises the measured performance against the specification.

Criteria	Specifications	Measured Performance	Passed
SPS SIS Accuracy	The User Range Error (URE) ≤7.8 m 95%	All SVs < 7.8m	Yes
SPS SIS rms	≤4 m	All days <4m	Yes
SPS SIS Integrity	The SIS Integrity $\leq 1x10^{-5}$ Probability Over Any Hour (<0.7 events per quarter)	No events	Yes
SPS SIS Continuity	≥ 0.9998 Probability Over Any Hour	100% (no unscheduled outages) 99.48% for rolling year	Yes, 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) 99.97% 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.

Criteria	Specifications	Measured Performance	Passed
PDOP Availability	• ≥ 98% global PDOP of 6 or less • ≥ 88% worst site PDOP of 6 or less	>99.8% availability on all days	Yes
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	• ≤ 9 meters 95% All-in-View Global Average Horizontal Error (SIS Only) • ≤ 17 meters 95% All-in-View worst site Horizontal Error (SIS Only) • ≤ 15 meters 95% All-in-View Global Average Vertical Error (SIS Only) • ≤ 37 meters 95% All-in-View worst site Vertical Error (SIS Only)	1) <3 metres 95% Horizontal Error at the site 2) <5 metres 95% Vertical Error at the site	Yes

Table 5-1: Summary of Performance

From the table it can be seen that the measured performance is within the required values for most requirements. The exception is the SIS continuity, which is below the threshold over the previous rolling year. That is due to one long unplanned outage in Q1 2018 causing the continuity to fall below the required performance threshold.

6 APPENDIX 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.

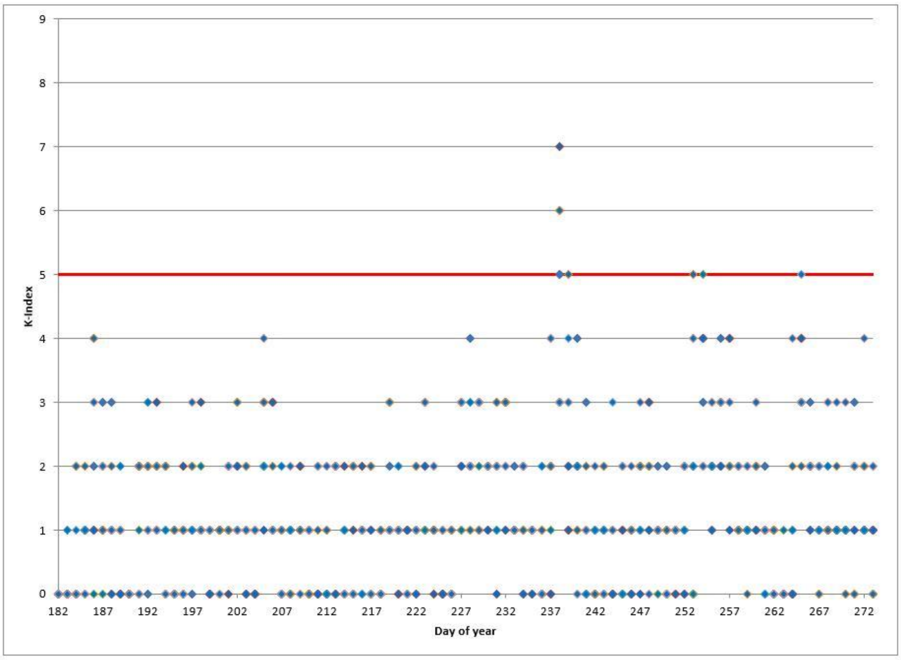

Figure 6-1: K-Index Values at Lerwick during Reporting Period

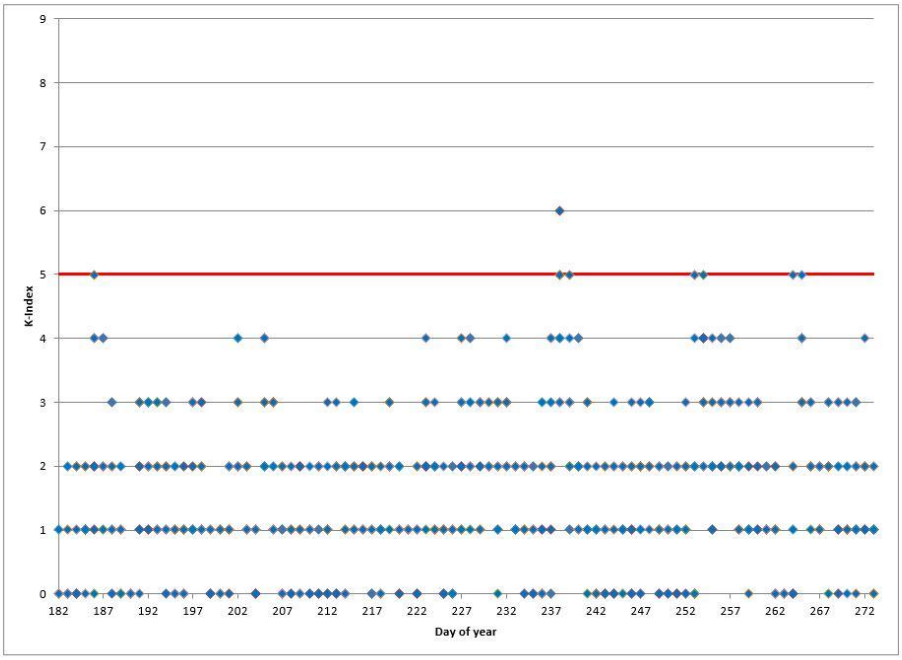

Figure 6-2: K-Index Values at Eskdalemuir during Reporting Period

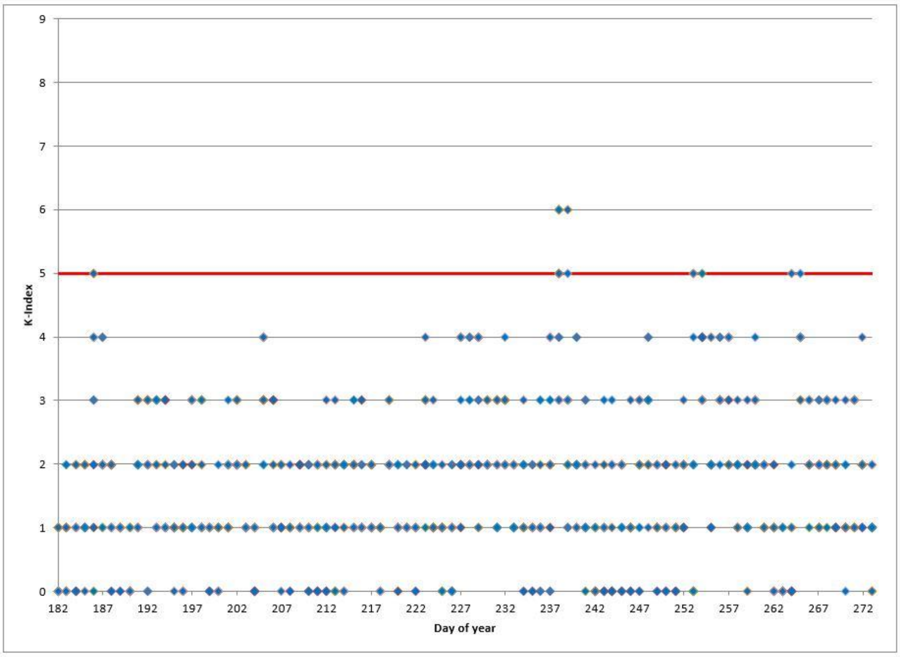

Figure 6-3: K-Index Values at Hartland during Reporting Period

It can be seen that during the monitoring period there are only a few occasions where geomagnetic storm conditions (K index >=5) are observed and generally it is a quiet period.

7 APPENDIX B: NAVIGATION DATA ISSUE

During this reporting period there were some strange results found during initial data processing at the start of September. For just over a week from 30th August there were occasions with very large position errors and RAIM failures.

Further investigation showed the large errors to be caused by degraded navigation message data. This affected many different satellites at different times rather than being linked to a specific satellite.

Rather than using navigation data directly from the LINO site, the data processing uses combined navigation messages obtained from merging data from a number of IGS sites. The idea is that by taking navigation data from many tens of IGS sites, navigation messages can be cross-checked between sites to ensure they are valid. This helps prevent the case where a receiver at a site has missing data, or outputs erroneous values. However, in this case it was found that a subset of the IGS sites were all outputting erroneous navigation data for some reason. All the sites were Javad receivers, whereas all sites that used other receiver types did not have this problem. As the erroneous navigation data seemed to be linked to a specific receiver type it was determined that this was a receiver problem rather than a true navigation message problem, and so the data was re-processed without the erroneous navigation data. The results and analysis in this document are therefore based on this corrected data.

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