



**GLOBAL POSITIONING SYSTEM (GPS)  
PERFORMANCE**

**JANUARY TO MARCH 2015**

**QUARTERLY REPORT**

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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 1 January 2015 to 31 March 2015. The objectives of the performance assessment are to compare the measured performance against US DoD SPS performance specification [RD.1], covering the following parameters:

- 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 according to [AD.1] and [AD.2] using raw data recorded at the OSi site SLGO.

## 1.2 Document Overview

This document is arranged in the following sections:

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

## 1.3 References

### 1.3.1 Applicable Documents

Ref.	Document title	Document reference	Issue	Date
AD.1	Purchase order – Performance Monitoring And Analysis Of GPS Signals	PO 201500179	-	-
AD.2	Outline Proposal to Ordnance Survey Ireland (OSi) in response to Request For Quotation for the provision of GPS performance monitoring services for Irish Aviation Authority (IAA)	OSI-GMAS-PRP	1.0	06/03/14

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	4 <sup>th</sup> Edition	Sept 2008
RD.2	Global Positioning System (GPS) Civil Monitoring Performance Specification	DOT-VNTSC-FAA-09-08	-	April 30 <sup>th</sup> 2009
RD.3	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
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HDOP	Horizontal Dilution Of Precision
IAA	Irish Aviation Authority
IGS	International GNSS Service
NANU	Notice Advisory to Navstar Users

<b>Acronym</b>	<b>Organisation</b>
NOTAM	Notice To Airmen
NSL	Nottingham Scientific Ltd
OSi	Ordnance Survey Ireland
PDOP	Position Dilution Of Precision
RAIM	Receiver Autonomous Integrity Monitoring
SIS	Signal In Space
SPS	Standard Positioning Service
TTA	Time To Alarm
URE	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	<p><b>The User Range Error (URE) for any healthy satellite for Single-Frequency C/A-Code:</b></p> <ul style="list-style-type: none"> <li>• <math>\leq 7.8</math> m 95% Global Average URE during Normal Operations over all age of data (AODs)</li> <li>• <math>\leq 6.0</math>m 95% Global Average URE during Normal Operations at Zero AOD</li> <li>• <math>\leq 12.8</math> m 95% Global Average URE during Normal Operations at Any AOD</li> <li>• <math>\leq 30</math> m 99.94% Global Average URE during Normal Operations over one year period</li> <li>• <math>\leq 30</math> m 99.79% Worst Case Single Point Average URE during Normal Operations over one year period</li> <li>• <math>\leq 388</math> m 95% Global Average URE during Extended Operations after 14 Days without Upload.</li> </ul> <p><b>The User Range Rate Error (URRE) for Single-Frequency C/A-Code:</b></p> <p><math>\leq 0.006</math> m/sec 95% Global Average URRE over any 3-second interval during Normal Operations at Any AOD</p> <p><b>The User Range Acceleration Error (URAE) for Single-Frequency C/A-Code:</b></p> <p><math>\leq 0.002</math> m/sec/sec 95% Global Average URAE over any 3-second interval during Normal Operations at Any AOD</p> <p><b>The UTC Offset Error for Single-Frequency C/A-Code:</b></p> <p><math>\leq 40</math> nsec 95% Global Average UTCOE during Normal Operations at Any AOD</p>

Criteria	Specifications
SPS SIS Integrity	<p><b>The SIS Integrity for Single-Frequency C/A-Code:</b></p> <ul style="list-style-type: none"> <li>• <math>\leq 1 \times 10^{-5}</math> Probability Over Any Hour of the SPS SIS Instantaneous URE Exceeding the NTE Tolerance Without a Timely Alert during Normal Operations</li> </ul> <p><b>The UTCOE Integrity for Single-Frequency C/A-Code:</b></p> <ul style="list-style-type: none"> <li>• <math>\leq 1 \times 10^{-5}</math> Probability Over Any Hour of the SPS SIS Instantaneous UTCOE Exceeding the NTE Tolerance Without a Timely Alert during Normal Operations</li> </ul>
SPS SIS Continuity	<p><b>SPS SIS Unscheduled Failure Interruption Continuity</b></p> <ul style="list-style-type: none"> <li>• <math>\geq 0.9998</math> Probability Over Any Hour of Not Losing the SPS SIS Availability from a Slot Due to Unscheduled Interruption</li> <li>• Given that the SPS SIS is available from the slot at the start of the hour</li> </ul>
SPS SIS Availability	<p><b>SPS SIS Per-Slot Availability</b></p> <ul style="list-style-type: none"> <li>• <math>\geq 0.957</math> Probability that a Slot in the Baseline 24-Slot Configuration will be Occupied by a Satellite Broadcasting a Healthy SPS SIS</li> <li>• <math>\geq 0.957</math> Probability that a Slot in the Expanded Configuration will be Occupied by a Pair of Satellites Each Broadcasting a Healthy SPS SIS</li> </ul> <p><b>SPS SIS Constellation Availability</b></p> <ul style="list-style-type: none"> <li>• <math>\geq 0.98</math> 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</li> <li>• <math>\geq 0.99999</math> 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.</li> <li>• <math>\geq 0.95</math> Probability that the Constellation will have at least 24 Operational Satellites regardless of Whether Those Operational Satellites are Located in Slots or Not.</li> </ul>
PDOP Availability	<ul style="list-style-type: none"> <li>• <math>\geq 98\%</math> global Position Dilution of Precision (PDOP) of 6 or less</li> <li>• <math>\geq 88\%</math> worst site PDOP of 6 or less</li> </ul>
SPS Position Service Availability	<ul style="list-style-type: none"> <li>• <math>\geq 99\%</math> Horizontal Service Availability average location</li> <li>• <math>\geq 90\%</math> Horizontal Service Availability worst-case location</li> <li>• <math>\geq 99\%</math> Vertical Service Availability average location</li> <li>• <math>\geq 90\%</math> Vertical Service Availability worst-case location</li> </ul>

Criteria	Specifications
	<b>With 17 m horizontal and 37 m vertical (SIS only) 95% threshold over 24hours</b>
Positioning Accuracy	<ul style="list-style-type: none"> <li>• ≤ 9 meters 95% All-in-View Global Average Horizontal Error (SIS Only)</li> <li>• ≤ 17 meters 95% All-in-View worst site Horizontal Error (SIS Only)</li> <li>• ≤ 15 meters 95% All-in-View Global Average Vertical Error (SIS Only)</li> <li>• ≤ 37 meters 95% All-in-View worst site Vertical Error (SIS Only)</li> <li>• ≤ 40 nanoseconds time transfer error 95% of time (SIS Only) for Time Transfer Domain Accuracy</li> </ul>

Table 2-1: SPS Criteria and Specifications

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

### SPS SIS Accuracy

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

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

### SPS SIS Integrity

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

- **Probability of a Major Service Failure.** The probability of a major service failure for the SPS SIS is defined to be the probability that the SPS SIS instantaneous URE exceeds the SIS URE NTE tolerance (i.e., MSI) without a timely alert being issued (i.e., unalerted MSI [UMSI]). Alerts generically include both alarms and warnings.
- **Time to Alert.** The time to alert (TTA) for the SPS SIS is defined to be the time from the onset of MSI until an alert (alarm or warning) indication arrives at the receiver's antenna. Real-time alert information broadcast as part of the NAV message data is

defined to arrive at the receiver's antenna at the end of the NAV message subframe which contains that particular piece of real-time alert information.

- SIS URE NTE Tolerance. The SPS SIS URE NTE tolerance for a healthy SPS SIS is defined to be 4.42 times the upper bound on the URA value corresponding to the URA index "N" currently broadcast by the satellite. The SIS URE NTE tolerance for a marginal SPS SIS is not defined and there is no SIS URE NTE tolerance for an unhealthy SPS SIS.

### **SPS SIS Continuity**

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

### **SPS SIS Availability**

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

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

### **PDOP Availability**

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

### **Position Service Availability**

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

### **Positioning Service Accuracy**

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

## **2.3 Methodology**

For the performance analysis in this report, raw GPS measurement data from reference stations has been analysed.

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

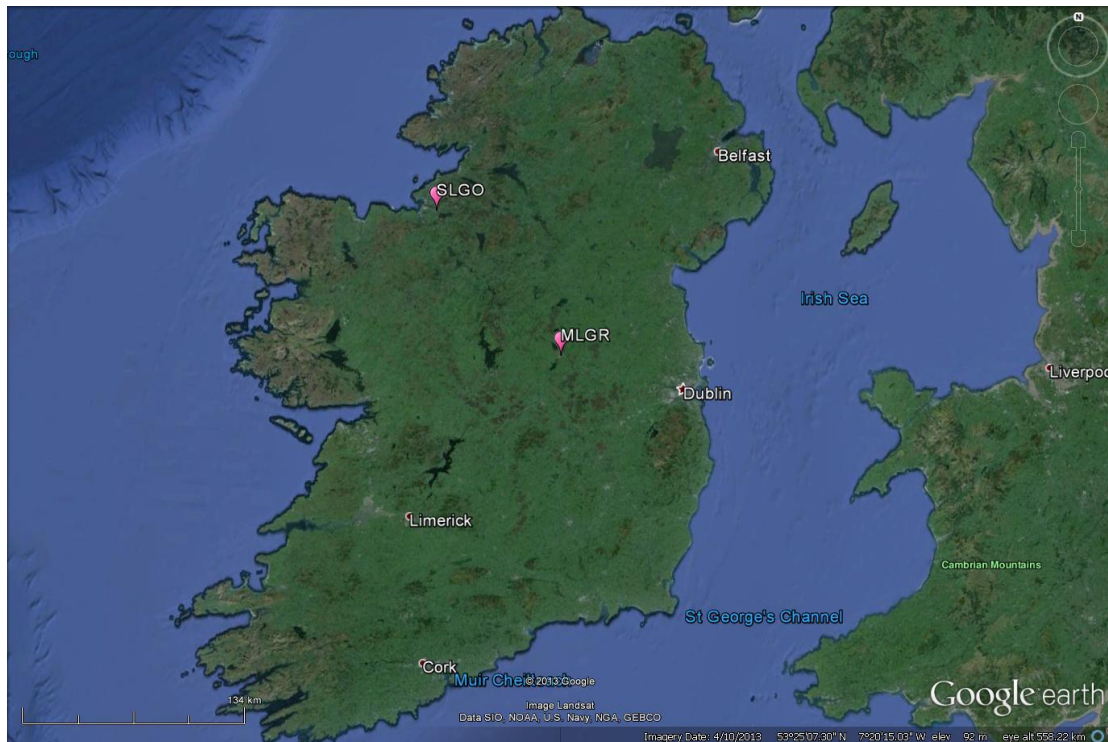


Figure 2-1: Location of Performance Monitoring Stations

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

- Centrally located within Ireland in order to ensure monitoring of complete airspace;
- Good data availability and continuity (i.e. avoid sites with historically poor data availability);
- Good measurement quality (i.e. avoid sites with known interference, multipath or sky visibility issues);
- Availability of required observation types and data.

In case there are problems with the data access simultaneously from both MLGR and SLGO, data from the EGNOS RIMS station at Cork will be used. The raw observation data is made available through the EGNOS Data Access Server (EDAS) in real-time or via an ftp archive.

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  $4.42 \times$  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 =  $1 \times 10^{-5}$  for

RAIM computations;

- UERE budget (non-SIS components) used in position solution and for RAIM predictions are given below [RD.4]:

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

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

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

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



### 3 SPS PERFORMANCE

#### 3.1 Baseline 24-Slot Constellation

The SPS SIS performance standard is largely based on the GPS baseline 24-slot constellation, which consists of 24 slots in six orbital planes with four slots per plane. 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 January 1 to March 31 2015.

Slot	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
PRN	24	31	-	7	16	25	28	12	29	27	19	17
Slot	D1	D2	D3	D4	E1	E2	E3	E4	F1	F2	F3	F4
PRN	2	1	21	4	3, 20	22	5	18	14	15	13	23

Table 3-1: Baseline constellation in the Period 01/01/15 to 27/01/15

Slot	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
PRN	24	31	30	7	16	25	28	12	29	27	19	17
Slot	D1	D2	D3	D4	E1	E2	E3	E4	F1	F2	F3	F4
PRN	2	1	21	6	20	22	5	18	14	15	9	23

Table 3-2: Baseline constellation in the Period 28/01/15 to 31/03/15

In this second period, PRN6 is swapped with PRN4 in slot D4, PRN9 is swapped with PRN13 in slot F3, PRN 30 is allocated slot A3 (which was previously empty) and PRN3 is allocated slot B6, leaving only PRN20 in slot E1. This means that there is now a fully defined baseline constellation of 24 SVs with no slot repetition.

#### 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 1 to March 31 2015 are shown in the next figure.

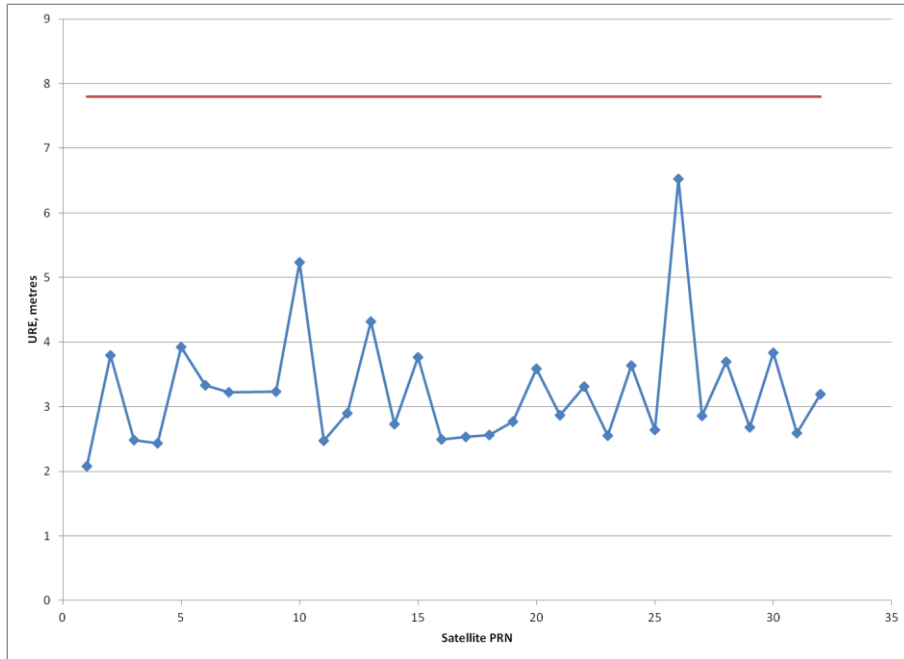


Figure 3-1: Constellation URE (95%) for Reporting Period

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 January to March 2015 and the 4m threshold are shown in the next figure. Note that  $\leq 7.8$  m 95% SPS SIS URE performance standard is equivalent to a  $\leq 4.0$  m RMS SPS SIS URE performance standard [RD.1]. This is also important for the position service availability assessment.

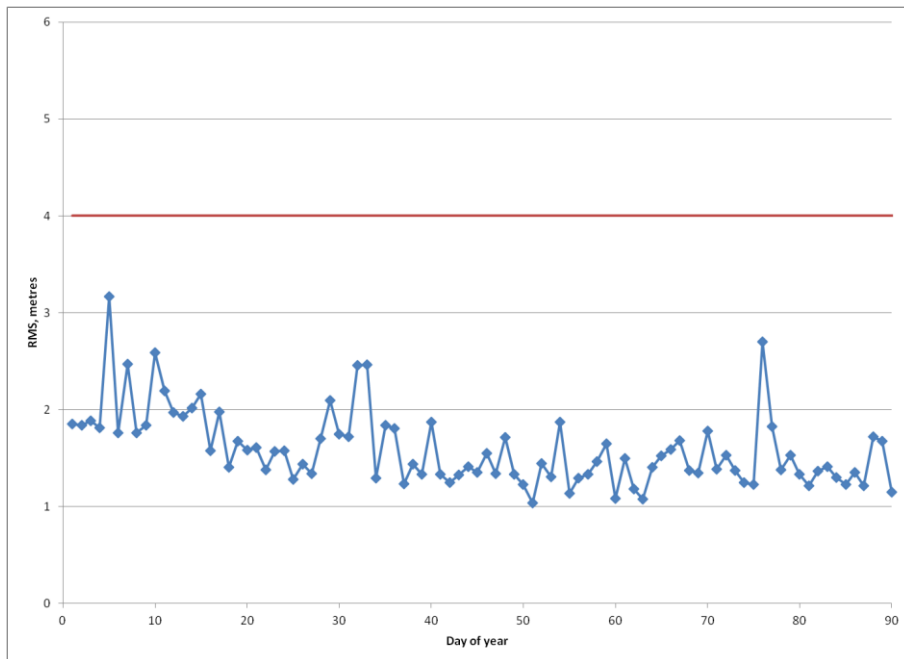


Figure 3-2: Constellation RMS URE for Reporting Period

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 January 1 to March 31 2015 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	-0.23	1.03	1.01	2.08	7.09	2189704
2	0.61	1.86	1.76	3.80	8.70	2813870
3	-0.50	1.26	1.15	2.49	7.74	2445544
4	0.14	1.21	1.20	2.43	5.35	2052211
5	0.13	2.05	2.05	3.93	8.60	2602284
6	-0.65	1.85	1.73	3.33	13.79	2658032
7	-0.27	1.60	1.58	3.22	7.88	2780979
8	NaN	NaN	NaN	NaN	NaN	0
9	0.35	1.64	1.60	3.23	8.89	2457559
10	1.26	2.65	2.33	5.23	9.91	2148782
11	0.68	1.30	1.11	2.47	9.01	1968220
12	0.02	1.51	1.51	2.90	11.91	2571917
13	0.61	2.17	2.09	4.32	8.47	2330989
14	0.34	1.42	1.38	2.73	8.94	2750465
15	0.52	1.86	1.78	3.77	10.37	2344665
16	0.49	1.36	1.27	2.49	10.24	2580250
17	-0.24	1.34	1.32	2.54	11.38	2832511
18	0.45	1.29	1.21	2.56	13.42	2846194
19	0.85	1.54	1.28	2.77	8.73	2423193
20	0.81	1.78	1.59	3.59	9.71	2084518
21	0.66	1.53	1.38	2.87	8.47	2760873
22	1.30	1.82	1.28	3.31	10.18	2824239
23	-0.05	1.34	1.34	2.55	9.35	2708002
24	0.53	1.87	1.79	3.64	12.25	2190245
25	0.40	1.46	1.40	2.64	12.95	2391472
26	2.59	3.42	2.24	6.53	9.15	115495
27	0.18	1.48	1.47	2.86	9.71	2329137
28	0.50	1.80	1.73	3.70	9.98	2800749
29	0.04	1.42	1.42	2.68	14.90	2670055
30	0.37	1.90	1.86	3.83	8.92	2700346
31	0.10	1.37	1.37	2.59	17.94	2732734
32	1.01	1.65	1.31	3.19	8.79	2506152

Table 3-3: Range Error Statistics for Reporting Period

Overall, the measured SIS accuracy meets the requirements during this 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  $\pm 4.42$  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  $1 \times 10^{-5}$ /hr probability for misleading information, 90 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 2 days where satellites have measured URE greater than the threshold value. These are days 7 and 76. These correspond to days where daily satellite URE is high and where 95% vertical errors are high. In addition, when processing the data in dual frequency mode these SIS error disappear, which suggests they are due to ionospheric residual errors rather than satellite SIS errors because SIS errors would affect dual-frequency results too.

For this reason, these days are not counted as failures for SIS Integrity and hence the requirement is passed.

It is also noted that on two days (18<sup>th</sup> Feb and 7<sup>th</sup> March) there were short periods lasting for 11 and 9 seconds respectively where the RAIM algorithm identified that the position solution contained a faulty measurement. However, further investigation of these issues found that the back-up site (MLGR) had no problems at these times, even though same satellites were in view. This suggests that there was a local problem at SLGO rather than a GPS system-wide problem.

### 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 and so the continuity for the baseline constellation is 100%, which meets the requirement of 99.98%.

### 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 52.85 hours. This is equivalent to an average of 0.999 over all slots in the 24-slot constellation, and satisfies SPS SIS Per-slot Availability standard ( $\geq 0.957$ ).

However, it should be noted that since 30<sup>th</sup> October PRN08 (which was in slot A3 of the baseline constellation) has been decommissioned and so has not been broadcasting at all. If this long period of 1497 hours is also included in the unavailability statistics the resulting value is 0.97, which still satisfies the SPS SIS Per-slot Availability standard ( $\geq 0.957$ ).

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.

- $\geq 0.98$  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;
- $\geq 0.99999$  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.

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

### 3.6 PDOP Availability

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

- Defined for position solution meeting the representative user conditions and operating within the service volume over any 24-hour interval;
- Based on using only satellites transmitting standard code and indicating “healthy” in the broadcast navigation message.

The following plot shows the daily PDOP availability (PDOP < 6) calculated at the site for all healthy satellites above 5 degrees elevation during the period January 1 to March 31 2015.

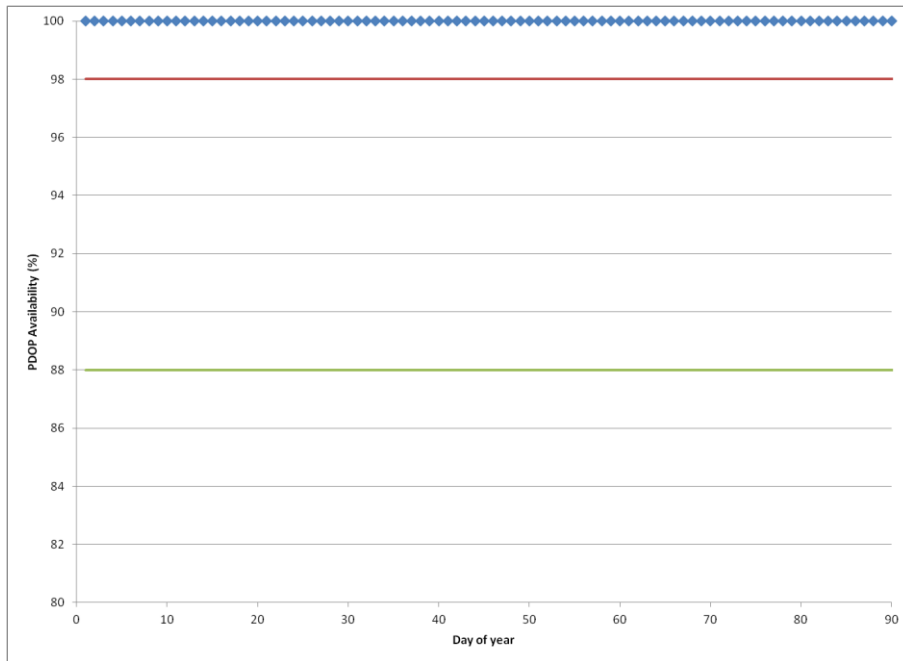


Figure 3-3: Daily PDOP Availability in the Reporting Period

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.

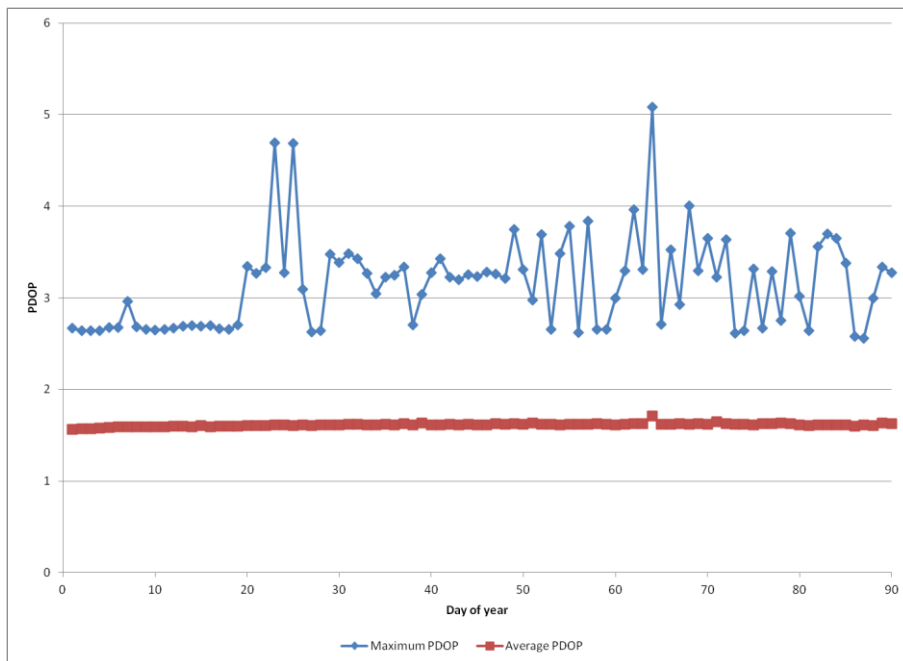


Figure 3-4: Daily Maximum PDOP Value in the Reporting Period

The daily PDOP values can be used to identify specific days that have different performance from the others. The first thing that can be seen is that the maximum PDOP is always well below 6 and most days have similar maximum and average values. There are some days that have higher maximum values but these days can be explained by individual satellites outages notified by NANU (e.g. day 64) or the receiver losing track of a satellite for a few seconds and leaving a slightly higher DOP for a few seconds.

### 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 January 1 to March 31 2015 are shown in the following figures.

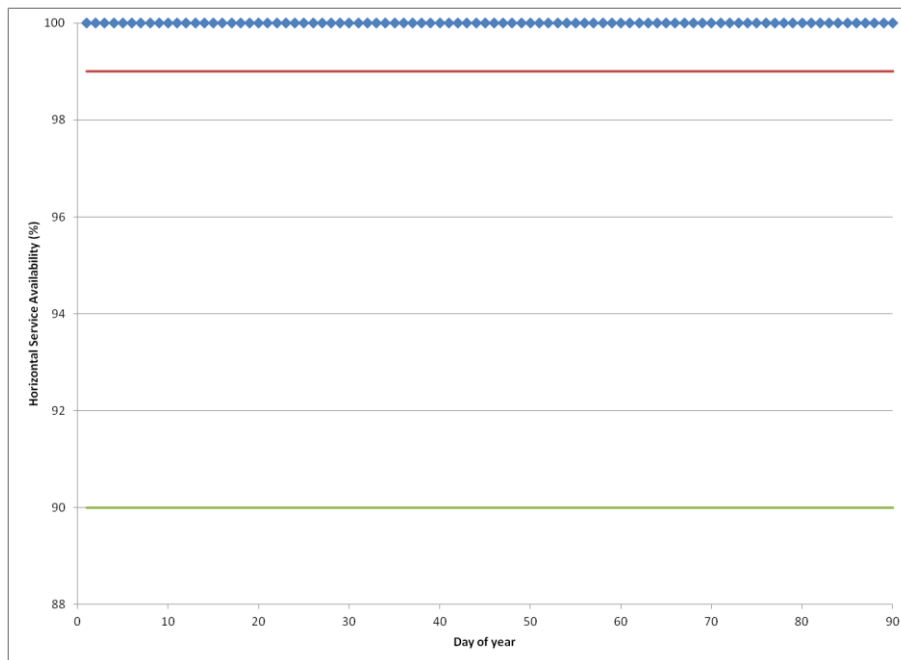


Figure 3-5: Daily Horizontal Service Availability Values for Reporting Period

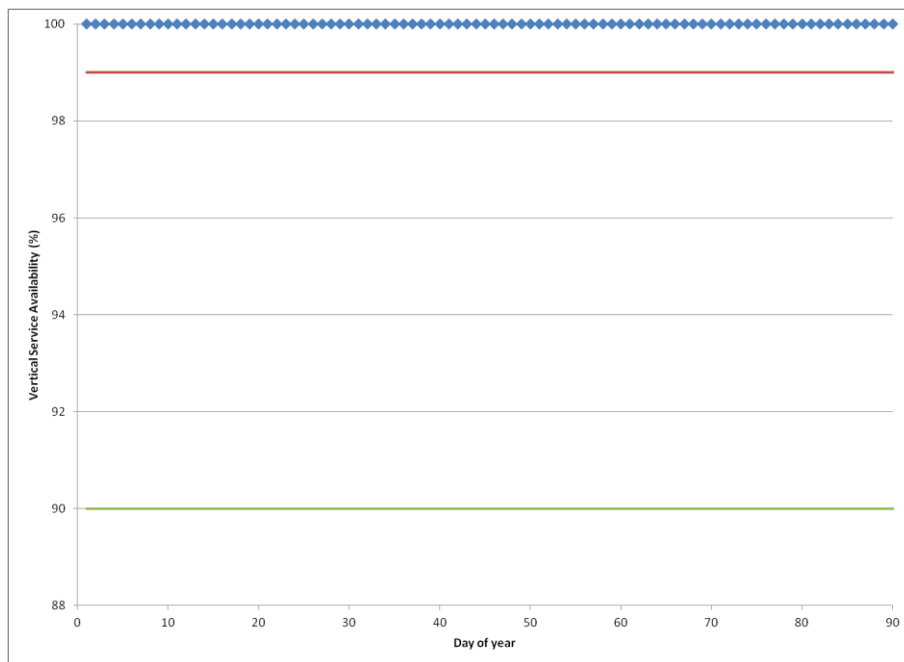


Figure 3-6: Daily Vertical Service Availability Values for Reporting Period

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 1 to March 31 2015 are shown in the following figures.



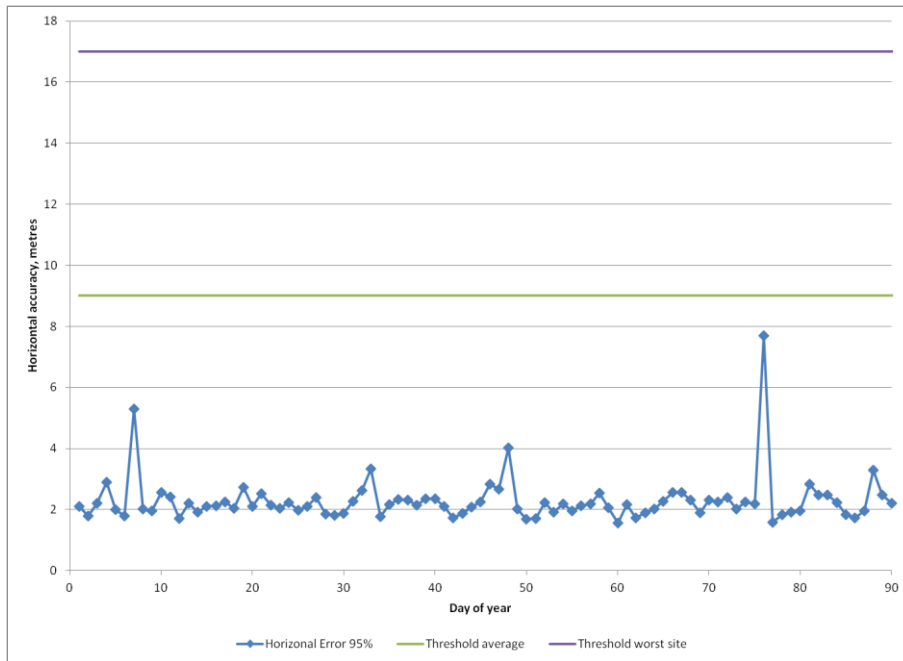


Figure 3-7: Daily Horizontal Position Accuracy (95%) for Reporting Period

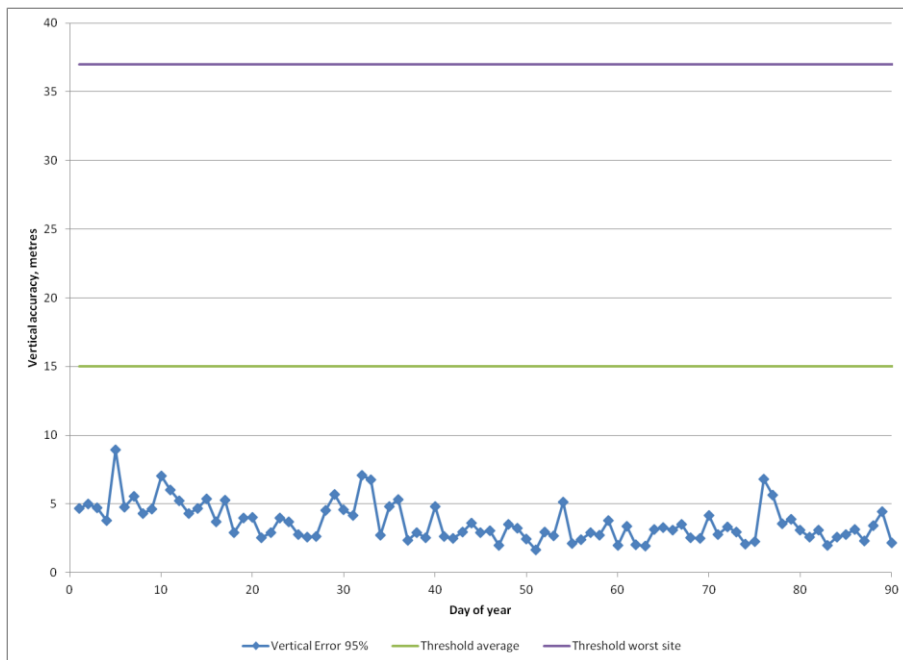


Figure 3-8: Daily Vertical Position Accuracy (95%) for Reporting Period

It can be seen that the daily horizontal accuracy values are all below the thresholds of 9m (global average) and 17m (worst site). Also the daily vertical accuracy values are 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.

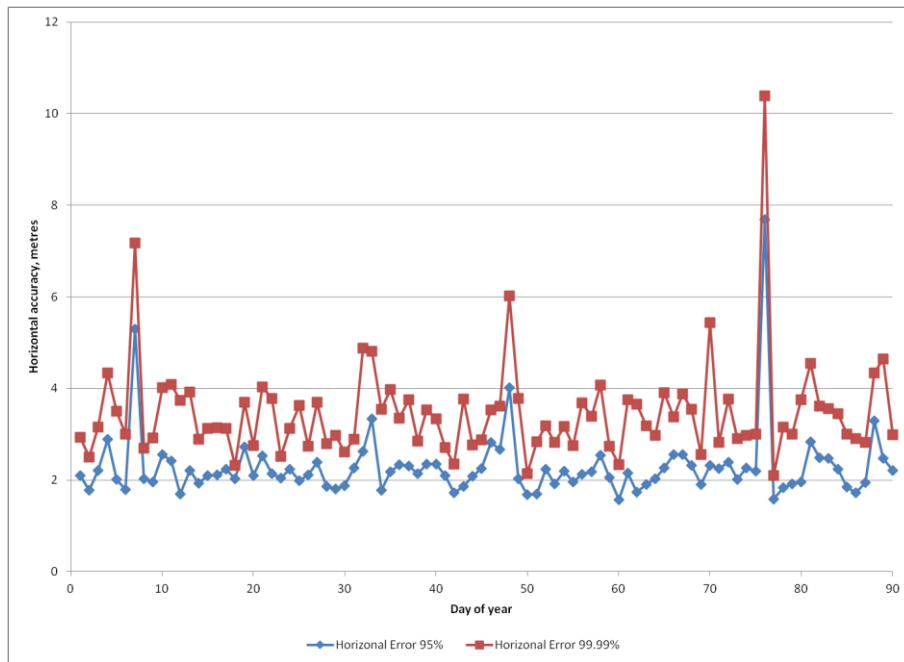


Figure 3-9: Daily Horizontal Position Accuracy (99.99%) for Reporting Period

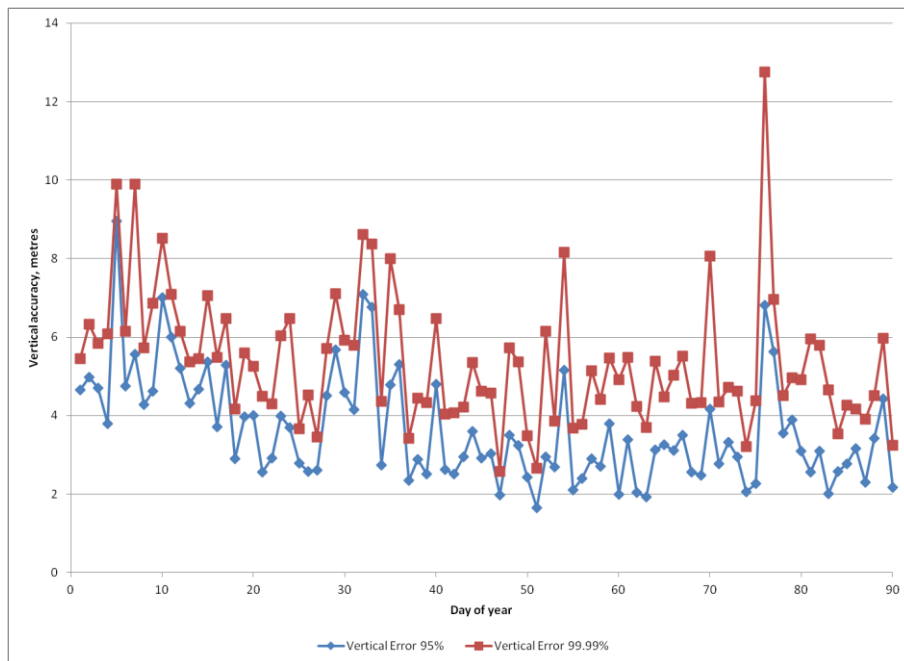


Figure 3-10: Daily Vertical Position Accuracy (99.99%) for Reporting Period

It can be seen that the 99.99% values generally follow the same pattern as the 95% values and are not significantly larger. This indicates there are no large outlying errors due to faulty behaviour and the performance is as expected.

## 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
2014093	13	FCSTDV	9	530	9	1730	12	F3
2015001	13	FCSTDV	9	530	9	1730	12	F3
2015002	26	FCSTUUFN	5	1600	N/A	N/A	N/A	F5
2015008	30	FCSTDV	37	30	37	1230	12	A3
2015013	14	FCSTDV	64	1500	65	300	12	F1
2015015	29	FCSTDV	71	400	71	1600	12	C1
2015017	32	FCSTDV	79	830	79	2030	12	E5
2015020	32	FCSTMX	88	2200	101	0	50*	E5

Table 4-1: Summary of Forecast Scheduled Outages

\* For NANU 2015020 the outage time refers to the time scheduled in this quarter and not the total outage time.

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2015006	13	FCSTSUMM	9	544	9	1330	7.766667	2015001
2015005	26	DECOM	5	1750	6	2200	4.166667	2015002
2015009	30	FCSTSUMM	37	112	37	556	4.733333	2015008
2015014	14	FCSTSUMM	64	1512	64	2128	6.266667	2015013
2015016	29	FCSTSUMM	71	431	71	1048	6.283333	2015015
2015018	32	FCSTSUMM	79	906	79	1525	6.316667	2015017
2015023	32	FCSTSUMM	89	5	90	2344	47.65	2015020

Table 4-2: Summary of Actual Scheduled Outages

It is noted that there was an unusable NANU (2015022) linked to NANU 2015020 that was also sent. However the times were incorrect and after querying it with the USCG Navigation Centre they confirmed NANU 2015022 had been sent in error.

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Ref
2014094	13	FCSTCANC	9	530	N/A	N/A	N/A

Table 4-3: Summary of Cancelled Outages

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2015004	26	UNUSUFN	5	1750	N/A	N/A	N/A	2015002*
2015011	11	UNUSUFN	50	450	N/A	N/A	N/A	D5

NANU	PRN	Type	Start day	Start Time	Stop day	Stop time	Outage (hours)	Ref
2015012	11	UNUSABLE	50	450	51	1445	33.916667	2015011

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

\* Note that NANU 2015004 appears to cover the same outage as that forecast in NANU 2015002 and it is not considered as unscheduled in this analysis.

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.

	Q1 2015
<b>hrs</b>	2160
<b>total forecast downtime (all)</b>	122.00
<b>total forecast downtime (baseline)</b>	60.00
<b>total actual scheduled downtime (all)</b>	83.18
<b>total actual scheduled downtime (baseline)</b>	25.05
<b>Scheduled satellite outage events (all)</b>	7
<b>Scheduled satellite outage events (baseline)</b>	4
<b>Unscheduled satellite outage events (all)</b>	1
<b>Unscheduled satellite outage events (baseline)</b>	0
<b>Total actual unscheduled downtime (all)</b>	33.92
<b>Total actual unscheduled downtime (baseline)</b>	0.00
<b>Total actual downtime (all)</b>	117.10
<b>Total actual downtime (baseline)</b>	25.05
<b>Availability (all)</b>	99.825
<b>Availability (baseline)</b>	99.952
<b>Continuity (baseline)</b>	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.

It is noted that after PRN08 was decommissioned on 30<sup>th</sup> October, there was no healthy satellite in slot A3 of the baseline constellation until 28<sup>th</sup> January when PRN30 was allocated this slot. If the period 1<sup>st</sup> to 28<sup>th</sup> January is taken as an outage for availability assessment this adds an extra 648 hrs to the scheduled baseline outage, and leads to an overall availability of 98.7% for the baseline constellation.

In terms of unscheduled outages, there was one in this period on PRN11. However, this was not part of the baseline constellation and so the continuity is 100%.

From analysis of the broadcast navigation messages it can be seen that all occurrences of unhealthy satellites were linked with NANUs. As well as the outages listed above, PRN26 (SVN71) was launched on 25<sup>th</sup> March 2015 although it is not yet been set healthy. Also, PRN08 was unhealthy throughout the monitoring period until it was finally decommissioned on day 85 (26<sup>th</sup> March 2015).

## 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) $\leq 7.8$ m 95%	All SVs < 7.8m	Yes.
SPS SIS rms	$\leq 4$ m	All days <4m	Yes.
SPS SIS Integrity	The SIS Integrity $\leq 1 \times 10^{-5}$ Probability Over Any Hour (<0.7 events per quarter)	Events on 2 days	Yes. Events most likely to be caused by ionospheric residuals (i.e. not SIS errors)
SPS SIS Continuity	$\geq 0.9998$ Probability Over Any Hour	100% (no unscheduled outages on baseline)	Yes
SPS SIS Availability	<p>SPS SIS Per-Slot Availability</p> <ul style="list-style-type: none"> <li><math>\geq 0.957</math></li> </ul> <p>SPS SIS Constellation Availability</p> <ul style="list-style-type: none"> <li><math>\geq 0.98</math> Probability that at least 21 Slots out of the 24 Slots will be healthy</li> <li><math>\geq 0.99999</math> Probability that at least 20 Slots out of the 24 Slots will be healthy</li> <li><math>\geq 0.95</math> Probability that the Constellation will have at least 24 Operational Satellites</li> </ul>	<p>1) 99.9% per-Slot Availability (97% if consider missing PRN08)</p> <p>2) 100% Constellation Availability</p> <p>3) 100% probability that the number of operational satellite is larger than 24.</p>	Yes – even if consider loss of PRN08 meaning slot A3 is empty for some of the period.

Criteria	Specifications	Measured Performance	Passed
PDOP Availability	<ul style="list-style-type: none"> <li>• <math>\geq 98\%</math> global PDOP of 6 or less</li> <li>• <math>\geq 88\%</math> worst site PDOP of 6 or less</li> </ul>	>99.8% availability on all days	Yes
SPS Position Service Availability	<ul style="list-style-type: none"> <li>• <math>\geq 99\%</math> Horizontal Service Availability average location</li> <li>• <math>\geq 90\%</math> Horizontal Service Availability worst-case location</li> <li>• <math>\geq 99\%</math> Vertical Service Availability average location</li> <li>• <math>\geq 90\%</math> Vertical Service Availability worst-case location</li> </ul>	100% availability on all days	Yes
Positioning Accuracy	<ul style="list-style-type: none"> <li>• <math>\leq 9</math> meters 95% All-in-View Global Average Horizontal Error (SIS Only)</li> <li>• <math>\leq 17</math> meters 95% All-in-View worst site Horizontal Error (SIS Only)</li> <li>• <math>\leq 15</math> meters 95% All-in-View Global Average Vertical Error (SIS Only)</li> <li>• <math>\leq 37</math> meters 95% All-in-View worst site Vertical Error (SIS Only)</li> </ul>	<p>1) Normally &lt;4 metres 95% Horizontal Error at the site, with one day up to 8m</p> <p>2) &lt;10 metres 95% Vertical Error at the site</p>	Yes

Table 5-1: Summary of Performance

From the table it can be seen that the measured performance is within the required values for all requirements.

Although there are some apparent SIS integrity issues, these are most likely caused by high ionospheric residual errors rather than SIS errors and so are not counted as failures.

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