



**INTEGRITY AND CONTINUITY ANALYSIS  
FROM GPS**

**APRIL TO JUNE 2011**

**QUARTERLY REPORT**

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Pages: 24

## Change Record

<b>Issue Rev</b>	<b>Date</b>	<b>§: Change Record</b>	<b>Author</b>
1.A	12/10/11	First version delivered to CAA for review and comment	M Pattinson
1.B	24/10/11	Final version delivered to CAA after addition of start times for HPL outage periods	M Pattinson

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# 1 Introduction

## 1.1 Purpose of Document

This document presents the results of the integrity and continuity analysis for GPS against ICAO requirements for the period of 1 April 2011 to 30 June 2011. The results have been generated in the frame of the performance monitoring contract awarded to NSL by the CAA. The objectives of the study are to compare the measured performance to applicable ICAO SARPs in Annex 10 Volume 1 [RD.1], covering the following parameters [AD.1]:

- Accuracy;
- Integrity;
- Continuity;
- Availability.

Assuming fault free receiver performance conforming to TSO-C129 specification.

The performance is analysed using raw GPS data recorded at 1Hz rate at the IGS Herstmonceux in the South of the UK.

## 1.2 Document Overview

This document is arranged in the following sections:

- **Section 1**, the current section, is an introduction which describes the purpose, scope and structure of the document;
- **Section 2** gives an introduction to the activity, including relevant performance requirements, methodology for assessment and list of assumptions;
- **Section 3** presents the accuracy assessment;
- **Section 4** contains an assessment of the integrity;
- **Section 5** presents the continuity assessment;
- **Section 6** contains an assessment of the availability;
- **Section 7** presents the conclusions.

## 1.3 References

### 1.3.1 Applicable Documents

Ref.	Document title	Document reference	Issue	Date
AD.1	Specification – Monitoring and Analysis of GPS Signals in Space	Contract no. 1673	0.4	24/11/10

**Table 1-1: Applicable Documents**

### 1.3.2 Reference Documents

Ref.	Document title	Document reference	Issue	Date
RD.1	ICAO SARPS, Annex 10: International Standards and Recommended Practices: Aeronautical Telecommunications, Volume 1: Radio Navigation Aids	-	6 <sup>th</sup> Edition	July 2006
RD.2	Global Positioning System Standard Positioning Service Performance Standard	GPS SPS	4 <sup>th</sup> Edition	Sept 2008
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

**Table 1-2: Reference Documents**

## 1.4 Acronyms

Acronym	Organisation
CAA	Civil Aviation Authority
CTI	Continuity Time Interval

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Acronym	Organisation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAL	Horizontal Alert limit
HPL	Horizontal Protection Level
ICAO	International Civil Aviation Organization
IGS	International GNSS Service
MTBF	Mean Time Between Failure
MTBO	Mean Time Between Outage
MTTR	Mean Time To Restore
NPA	Non-Precision Approach
NSL	Nottingham Scientific Ltd
RAIM	Receiver Autonomous Integrity Monitoring
RTCA	Radio Technical Commission for Aeronautics
SARPS	Standards and Recommended Practices
SIS	Signal In Space
SPS	Standard Positioning Service
TTA	Time To Alarm
UERE	User Equivalent Range Error

**Table 1-3 : Acronyms and Abbreviations**

## 2 Introduction

### 2.1 Purpose

The purpose of the performance monitoring activity [AD.1] is to collect and analyse data on the performance of the GPS Signal In Space (SiS). For this report, the applicable requirements are defined in the ICAO SARPs (Standards and Recommended Practices) contained in Annex 10 to the Convention on International Civil Aviation, Volume 1 Radio Navigation Aids [RD.1].

### 2.2 ICAO Standards and Definitions

The ICAO Annex 10 Volume 1 Chapter 3 Section 3.7 details the ICAO SARPs for GNSS [RD.1]. Section 3.7.2.4.1 sets the Signal-in-Space (SiS) performance requirements. An important assumption made in this respect is that *“the combination of GNSS elements and a fault-free receiver shall meet the SiS requirements defined in Table 3.7.2.4- 1 (located at the end of section 3.7)”*. The table below presents the requirements specified for NPA together with a number of corresponding notes.

Horizontal Accuracy 95% (Notes 1 and 3)	Horizontal Alert Limit	Integrity	Time to Alert (Note 3)	Continuity (Note 4)	Availability (Note 5)
220m	556m	$1-1 \times 10^{-7}/h$	10 s	$1-1 \times 10^{-4}/h$ to $1-1 \times 10^{-8}/h$	0.99 to 0.99999

**Note 1** – The 95<sup>th</sup> percentile values for GNSS position errors are those required for the intended operation at the lowest height above threshold (HAT), if applicable.

**Note 3** – The accuracy and time-to-alert requirements include the nominal performance of a fault free receiver.

**Note 4** – Ranges of values are given for the continuity requirement for NPA operations, as this requirement is dependent upon several factors including the intended operation, traffic density, complexity of airspace and availability of alternative navigational aids. The lower value given is the minimum requirement for areas with low traffic density and airspace complexity.

**Note 5** – A range of values is given for the availability requirement as these requirements are dependent upon the operational need which is based upon several factors including the frequency of operations, weather environments, the size and duration of outages, availability of alternative navigational aids, radar coverage, traffic density and reversionary operational procedures. The lower values given are the minimum availabilities for which a system is considered to be practical but are not adequate to replace non-GNSS navigation aids. For approach and departure, the higher values given are based upon the availability requirements

*at airports with a large amount of traffic assuming that operations to or from multiple runways are affected but reversionary operational procedures ensure the safety of the operation.*

Some related definitions for the performance requirements are given below.

### **Horizontal Accuracy**

Annex 10 Volume 1 Attachment D section 3.2.1 states: *“GNSS position error is the difference between the estimated position and the actual position. For an estimated position at a specific location, the probability should be at least 95 per cent that the position error is within the accuracy requirement.”*

### **Integrity, Horizontal Alert Limit, Time to Alert**

ICAO Annex 10 Volume 1 Attachment D section 3.3.1 states: *“Integrity is a measure of the trust that can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of a system to provide timely and valid warnings to the user (alerts) when the system must not be used for the intended operation (or phase of flight).”* Therefore, integrity is the probability of not using a radiated false guidance signal.

For a loss of integrity to occur, the following conditions need to exist at the same time:

- radiation from the satellite system of a signal, which would result in a derived position error outside the ICAO GNSS NPA Horizontal Alert Limit (HAL), and
- failure to detect and indicate when the ICAO GNSS NPA HALs have been exceeded for a period of time beyond the ICAO GNSS NPA Time-To-Alert (TTA) period.

In this respect, the following points are relevant:

- The GPS SPS [RD.2] incorporates monitoring of the health of the satellites. This monitoring is not at the required probability level nor is it sufficiently prompt to fulfil the ICAO GNSS Horizontal Accuracy and TTA requirements.
- The use of at least a TSO-C129a compliant receiver will be necessary for GPS supported NPAs in accordance with AMC-20-XX. This type of receiver provides “Real-time monitoring” of the derived GPS position by the use of Receiver Autonomous Integrity Monitoring (RAIM).
- The requirements for the integrity contribution of the receiver are specified in document RTCA DO-208 Table 2-1 “GPS Position Integrity Performance Requirements”, which is referenced from document TSO-C129a. Table 2-1 sets a minimum detection probability at 0.999.
- The ICAO requirement for integrity for GPS when used to provide a NPA is  $1 - (1 \times 10^{-7})$  per flight hour.
- Taking into account the receiver detection probability of 0.999 there remains an integrity requirement of  $1 - (1 \times 10^{-4})$  per flight hour to be achieved by the remaining parts of the system. These remaining parts include the

performance of the SIS and any other real time monitoring devices in use.

### **Continuity**

Annex 10 Attachment D section 3.4.1 states: “*Continuity of service of a system is the capability of the system to perform its function without unscheduled interruptions during the intended operation.*” ICAO provides a range of values for continuity; the value used by a specific aerodrome will depend upon several factors including the intended operation, traffic density, complexity of airspace and availability of alternative navigational aids. Guidance on setting this requirement can be found in Annex 10 Volume 1 Attachment D section 3.4.2.3

It should be noted that the ICAO SARPs for NPA are consistent with those for en-route. In this respect, Annex 10 Volume 1 Attachment D section 3.4.2.1 states: “*For en-route operations, continuity of service relates to the capability of the navigation system to provide a navigation output with the specified accuracy and integrity throughout the intended operation, assuming that it was available at the start of the operation.*”

Therefore, loss of continuity (strictly in the case of SiS, i.e. assuming a fault free receiver) can be considered to be when the horizontal alert limit cannot be achieved due to an unexpected failure of the GPS service for 10 Seconds or more, during a period when RAIM is predicted to be available for a specific approach.

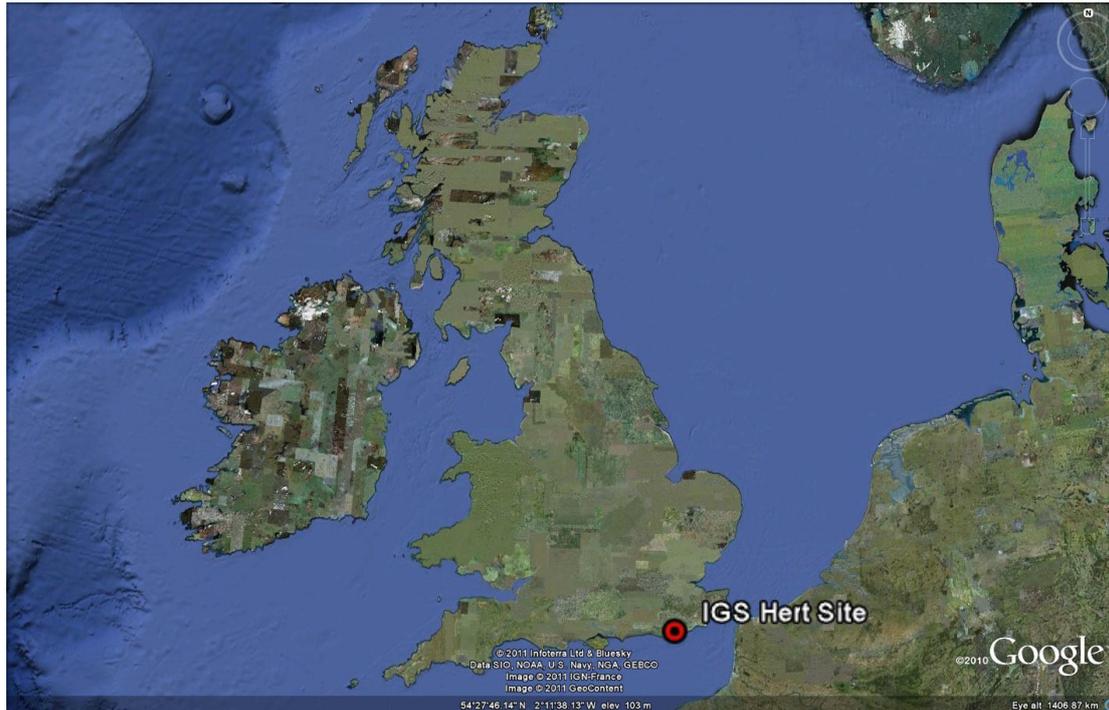
### **Availability**

ICAO Annex 10 Volume 1 Attachment D section 3.5.1 states: “*The availability of GNSS is characterized by the portion of time the system is to be used for navigation during which reliable navigation information is presented to the crew, autopilot, or other system managing the flight of the aircraft*”. Furthermore, Section 3.5.6 states: “*The availability of GNSS should be determined through design, analysis and modelling, rather than measurement.*”

Under normal conditions, availability of the signal from sufficient satellites for the provision of RAIM, a prerequisite for the use of GPS in support of a NPA, is predictable and may be assessed in advance of the use of the instrument approach procedure.

## **2.3 Methodology**

For the performance analysis in this report, raw data from the Hert IGS site in the South of the UK is analysed. The location of the site is shown in the following Google Earth plot.



**Figure 2-1: 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 combined daily broadcast navigation message files are also downloaded from the IGS ftp site and used to provide the navigation data [RD.4].

It should be noted that this site has been used due to the availability of 1Hz data for the period in question. In future reports there may be other sites located more centrally within the UK for which 1Hz data is available (e.g. Ordnance Survey Active Stations).

Using the raw L1 (C/A) data, the GISMO processing SW computes a position solution on every epoch, as well as a Horizontal Protection Level. The position solution on each epoch is then compared against the precise surveyed location of the antenna in order to generate position errors. These values are then used in the analysis of accuracy, integrity, continuity and availability.

## **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;
- 10 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;

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- 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 based given below [RD.3]:

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

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

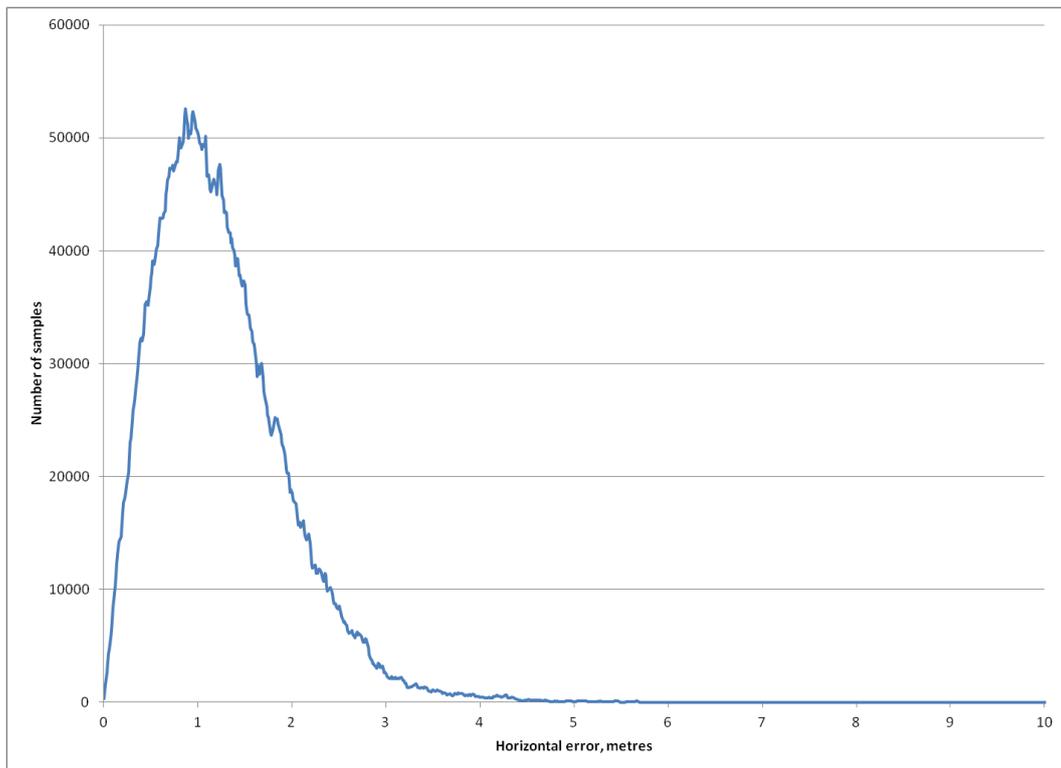
As the actual monitoring is based on the measurements from one receiver, the following points should be noted:

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

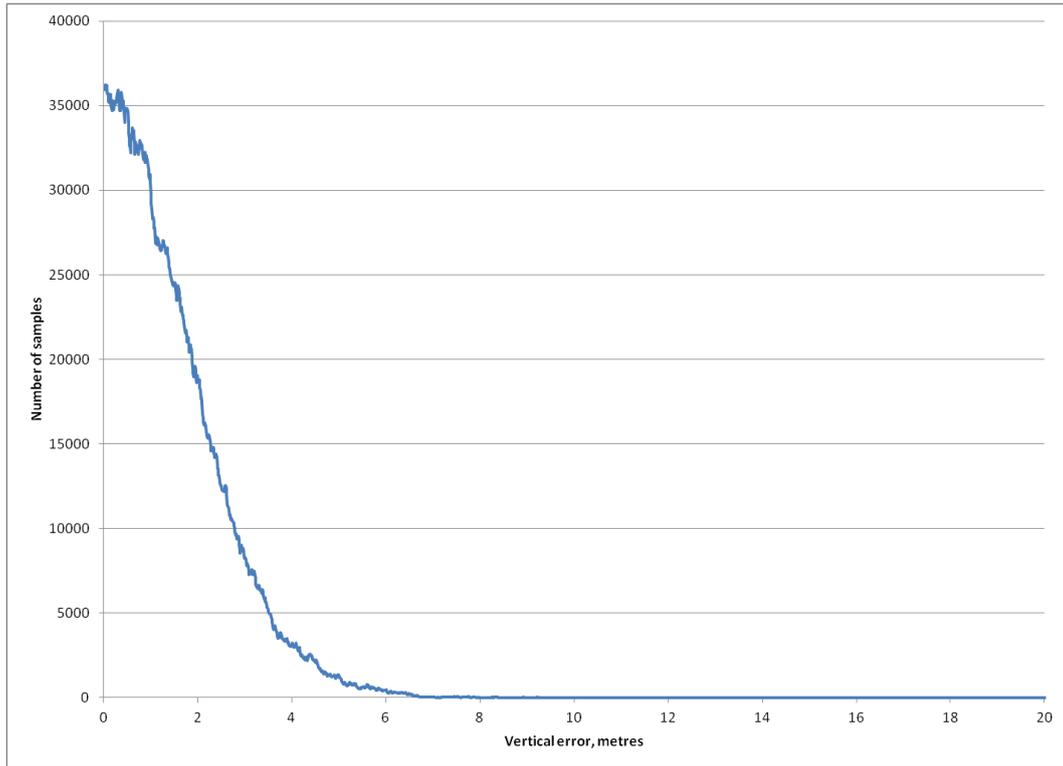
### 3 Accuracy

Accuracy is defined as the measure of the calculated position error between the position solution and the known location of the antenna at the 95th percentile. The position solution is computed at the receiver using the L1 GPS measurements at 1Hz rate above an elevation of 10 degrees.

The horizontal and vertical error distributions for the period April 1 to June 30 2011 are shown in the following figures. The samples shown in each figure are in error bins of 1cm and include position errors from all days during the monitoring period.



**Figure 3-1: Horizontal Error Distribution for Monitoring Period**



**Figure 3-2: Vertical Error Distribution for Monitoring Period**

It can be seen that the horizontal errors are most commonly around 1 to 2m.

To better understand the maximum errors, details of the horizontal error distribution above 5m and vertical error distribution above 8m are also shown.

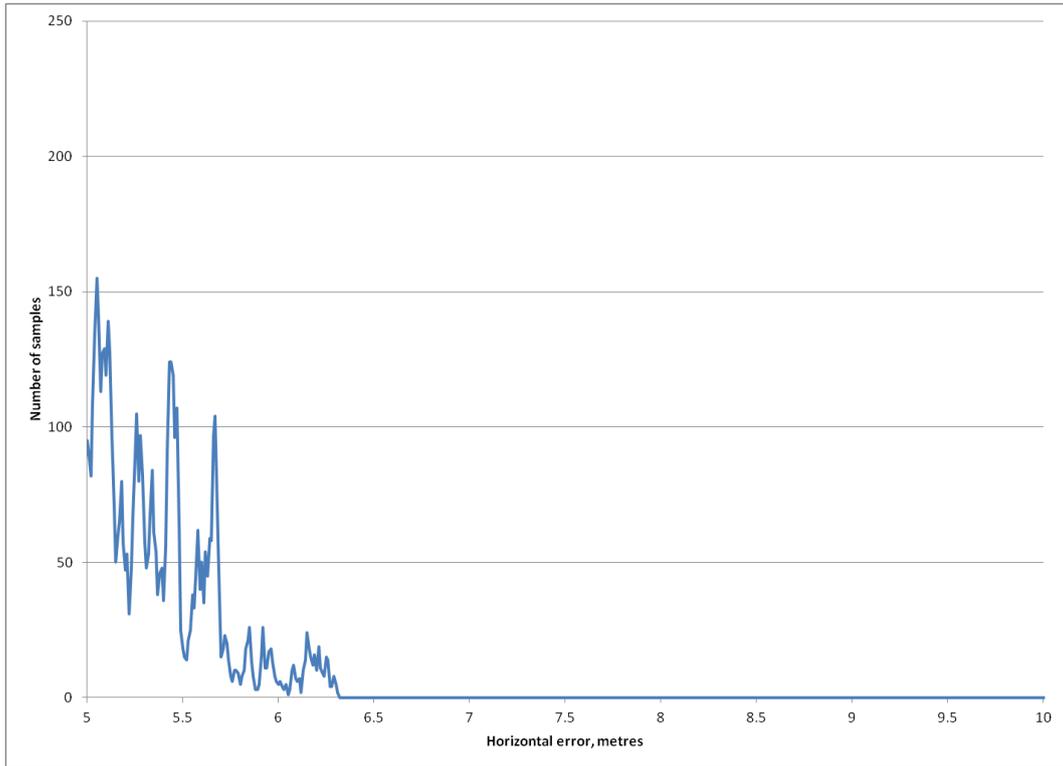


Figure 3-3: Horizontal Error Distribution above 5m for Monitoring Period

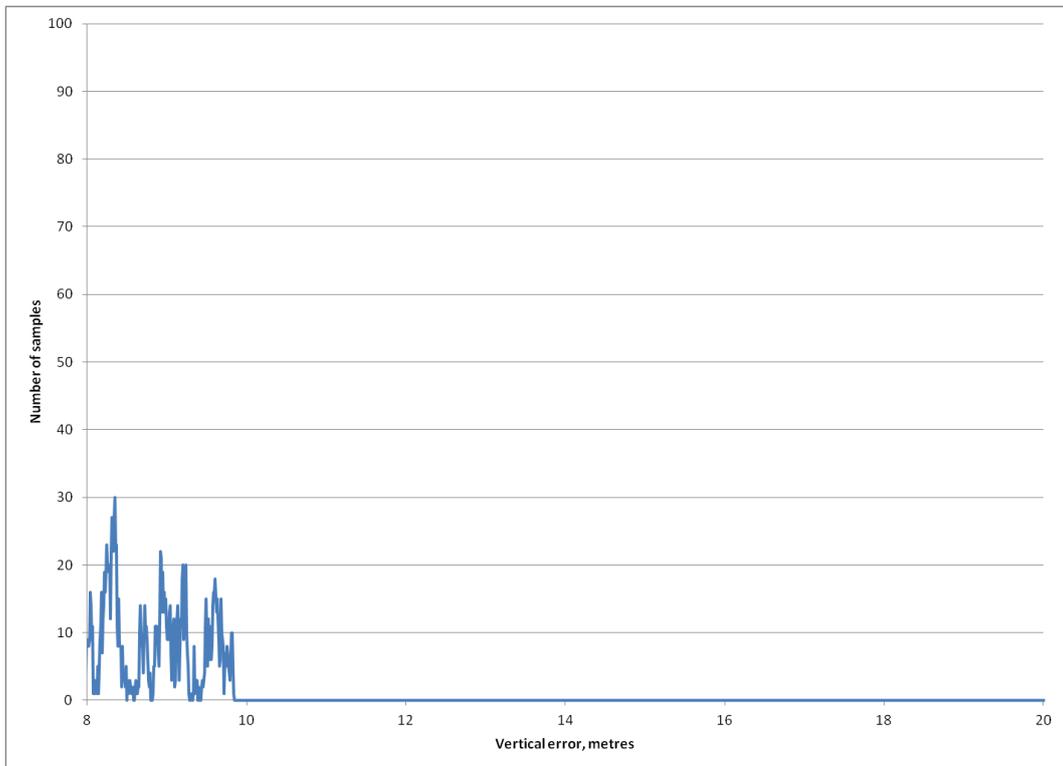


Figure 3-4: Vertical Error Distribution above 8m for Monitoring Period

It is clear from the results that the maximum horizontal errors are well below the

accuracy requirement for Non Precision Approach (220m, 95%).

The daily 95% position errors are also shown to illustrate the fact that the daily performance is also well within the requirement.

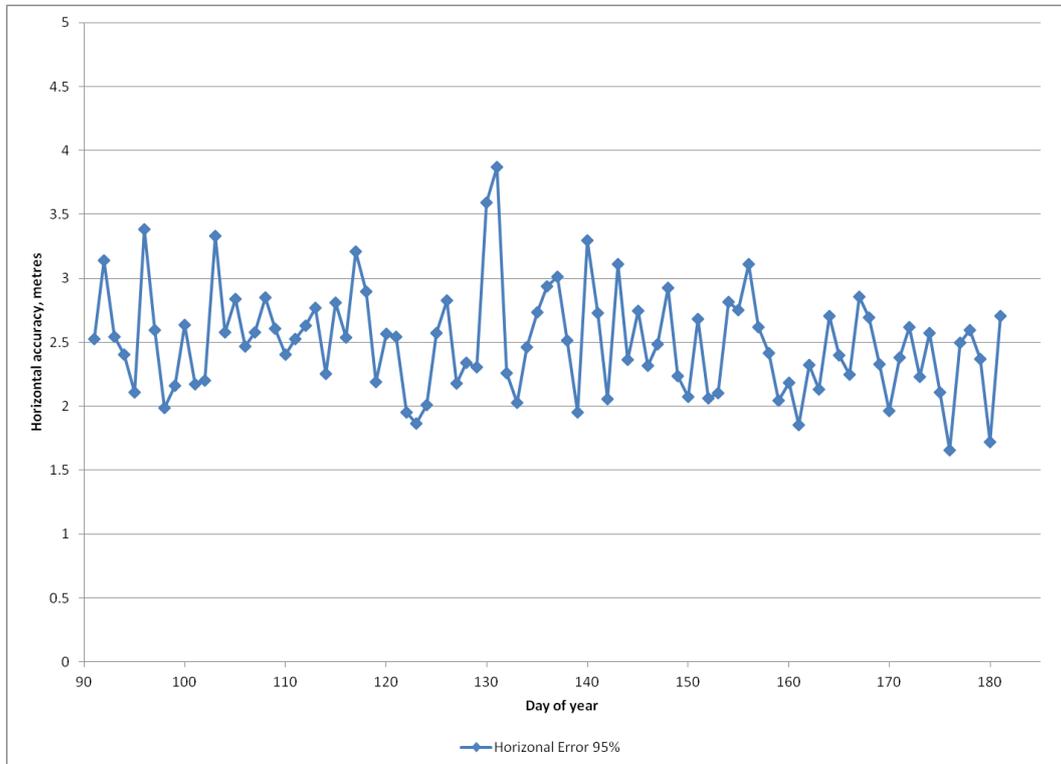


Figure 3-5: Horizontal Position Accuracy (95%) for Monitoring Period

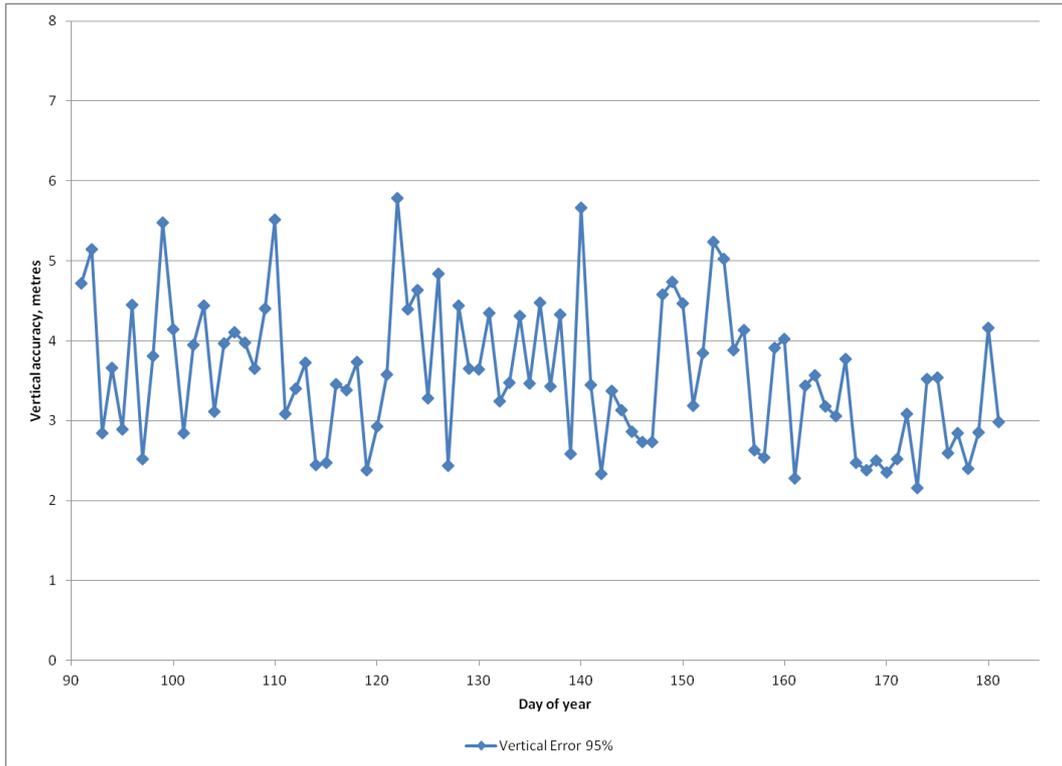


Figure 3-6: Horizontal Position Accuracy (95%) for Monitoring Period

## 4 Integrity

The approach taken here is as stated in Section 1.2, with the integrity data generated based on the known positions of the antennas. The basic assumption made is that the receiver is fault free and that its integrity function has a probability of missed detection (Pmd) of 0.001. The process adopted here involves firstly mapping the ICAO requirements to the period under investigation to enable the determination of compliance with ICAO requirements. Given the Pmd of 0.001 and that the integrity risk for NPA is specified as  $1 \times 10^{-7}$  per hour, the SiS probability of failure is determined as  $1 \times 10^{-4}$  per hour. Because of the effect of dynamics and/or contextual factors on aircraft attitude, it is assumed that there are 3600 independent measurements in any given hour. This translates to a probability of failure of  $2.78 \times 10^{-8}$  per sample. Therefore, for the period analysed (i.e. 7862400 samples) the maximum allowable number of failures is 0.22.

The next step compares the positioning solutions as determined from the measurements and the known positions of the antenna. The resulting position errors are then compared to the alert limit for NPA. Finally, the number of violations (the cases where the position errors are larger than the alert limit) is compared to the maximum allowable number of failed satellites (i.e. 0.22). It is on this basis that compliance (or non-compliance) with ICAO's integrity requirements has been determined. It should be noted that this is a rather simple approach as it does not account for the uncertainties in the quantities being compared, particularly in the case of position solutions and the coordinates of the antennas. However, as the Alert Limit is large compared to the normal level of positioning error it is a reasonable approximation.

The distributions of horizontal and vertical errors for the period April 1 to June 30 2011 were shown in section 3. It was seen that the horizontal errors were usually around 1-2m with a maximum value of <6.5m. As there are no horizontal position errors that are even close to 556m, this means that the integrity requirement was met during the monitoring period.

## 5 Continuity

The continuity in the monitoring period is computed as:

$$continuity = 1 - \frac{CTI}{MTBF}$$

Where CTI is the continuity time interval (1hr in this case),

MTBF is the mean time between failures, which is computed as total time divided by number of failure events.

A failure event is counted as any period lasting for more than 10 seconds where:

- HPL cannot be computed (i.e. <5 satellites in view above elevation mask);
- Computed HPL > Alert Limit (i.e. 556m);
- Computed horizontal position error > Alert Limit;
- Any combination of the above.

It should be noted that continuity only considers failures due to unscheduled events, and so any periods of high HPL for example that have been previously informed via a NANU are not counted as a failure for continuity.

During the monitoring period of April 1 to June 30 2011 there were no epochs with <5 satellites in view above the elevation mask and no instances of the horizontal position error exceeding the alert limit (556m). However, there were some other possible failure events that were observed.

- Day 133 (13<sup>th</sup> May): 42 epochs with HPL > 556m, from 23:06:37;
- Day 134 (14<sup>th</sup> May): 37 epochs with HPL > 556m, from 23:02:40;
- Day 135 (15<sup>th</sup> May): 34 epochs with HPL > 556m, from 22:58:42;
- Day 136 (16<sup>th</sup> May): 30 epochs with HPL > 556m, from 22:54:45;
- Day 137 (17<sup>th</sup> May): 26 epochs with HPL > 556m, from 22:50:47;
- Day 138 (18<sup>th</sup> May): 23 epochs with HPL > 556m, from 22:46:49;
- Day 139 (19<sup>th</sup> May): 18 epochs with HPL > 556m, from 22:42:52;
- Day 140 (20<sup>th</sup> May): 13 epochs with HPL > 556m, from 22:38:55;
- Day 141 (21<sup>st</sup> May): 9 epochs with HPL > 556m, from 22:34:58;
- Day 142 (22<sup>nd</sup> May): 3 epochs with HPL > 556m, from 22:31:02;

After further analysis it is seen that all these outages occur around the same time each day and are related to the NANU for PRN30. On day 132, where PRN30 is healthy, the same period has 7 satellites in view and no HPL problems. From day 133 onwards, PRN30 is missing during this period leaving only 6 satellites and the HPL values exceed the threshold for short periods. The outages last for less and less time each day as the geometry slowly changes.

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If we consider outages >10 seconds there are 8 in total. As they are all related to the PRN30 outage, which was unscheduled, it could be said that all will affect continuity.

With these 8 failures the MTBF is computed as  $91 \times 24 / 8 = 273$  hrs and the continuity over this period is  $1 - 1/273 = 0.9963$ , which does not meet the continuity requirement of 0.9999 to 0.99999999.

An alternative could be to say that after 2 days being unusable (the time normally required before an event for a scheduled NANU), the outage no longer contributes to continuity. In this case there would only be 2 outages and the MTBF is computed as  $91 \times 24 / 2 = 1092$  hrs and the continuity over this period is  $1 - 1/1092 = 0.9991$ , although this still does not meet the continuity requirement.

However, it should be noted that the continuity figure should be computed over a year long period in order to give representative results and so the requirement will not be fully verifiable until 1 year of analysis has been completed.

It should also be noted that if a lower elevation mask had been used (e.g. 7.5 degrees) these failure would not have occurred because there would have been more satellites in view during the outage period (PRNs 29 and 22 are just below 10 degrees at this time) and the HPL values would not have exceeded the threshold.

## 6 Availability

The availability in the monitoring period is computed as:

$$availability = \frac{MTBO}{MTBO + MTTR}$$

Where MTBO is the mean time between outage, which is computed as total time divided by number of outage events, and

MTTR is the mean time to restore, which is computed as total outage time divided by number of outage events.

In the same way as for continuity analysis, outages are identified and used to compute the MTBO and MTTR figures. The difference in this case is that availability includes outages due to scheduled as well as unscheduled outages.

Based on the list of outages from the previous section it can be seen that during this period there are 8 outages > 10 seconds with a total time of 223 seconds. With these 8 failures the MTBO is computed as  $91 \times 24 / 8 = 273$  hrs and the MTTR is 27.88 seconds (or 0.0077 hrs). Therefore the availability over this period is  $273 / (273 + 0.0077) = 0.99997$ , which would meet the availability for some operations but not the upper level of 0.99999 in the standards.

However, it should be noted that the availability figure should be computed over a year long period in order to give representative results and so the requirement will not be fully verifiable until 1 year of analysis has been completed.

It should also be noted that if a lower elevation mask had been used (e.g. 7.5 degrees) the number, and duration, of outages would have been significantly reduced because there would have been more satellites in view during the outage periods and the HPL values would not have exceeded the threshold so often.

## 7 Conclusions

The GPS performance has been assessed against the ICAO requirements for the period of April to June 2011.

- Accuracy
  - Horizontal accuracy checked against threshold of 220m.
  - 95% horizontal accuracy <4m on each day and maximum values <6.5m.
  - Accuracy requirement is passed.
- Integrity
  - Horizontal error checked against alert limit of 556m.
  - Maximum horizontal errors <6.5m, i.e. threshold is not exceeded.
  - Integrity requirement is passed.
- Continuity
  - Results checked for outages (<5 satellites, position error > alert limit, protection level > alert limit).
  - 8 periods where HPL > alert limit (for more than 10 seconds) due to unscheduled outage.
  - Continuity requirement not met because of these outages. However:
    - Representative figures only will be available after 1 year of data.
    - If lower elevation mask had been used, there would not have been any outages.
- Availability
  - Results checked for outages (<5 satellites, position error > alert limit, protection level > alert limit).
  - 8 periods where HPL > alert limit due to scheduled and unscheduled outages.
  - Availability requirement not met in all cases because of these outages. However:
    - Representative figures only will be available after 1 year of data.
    - If lower elevation mask had been used, there would have been no outages.

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