INTEGRITY AND CONTINUITY ANALYSIS FROM GPS

JULY TO SEPTEMBER 2019

QUARTERLY REPORT 3

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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 July to September 2019. 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 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, is an introduction which describes the purpose, scope and structure of the document;
- **Section 2** introduces 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	THE PROVISION OF MONITORING AND ANALYSIS OF GPS SIGNALS IN SPACE –	CONTRACT NO. 1762 (AMENDMENT NO. 7)	-	08/02/19

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	-	6th Edition	July 2006
RD.2	Global Positioning System Standard Positioning Service Performance Standard	GPS SPS	4th 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
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

Acronym	Organisation
NANU	Notice Advisory to Navstar Users
NOTAM	Notice To Airmen
NSL	Nottingham Scientific Ltd
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 [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	$1\text{-}1 \times 10^{-7}$/h	10 s	$1\text{-}1 \times 10^{-4}$/h to $1\text{-}1 \times 10^{-8}$/h	0.99 to 0.99999

***Note 1** – The 95th 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 $1-(1x10^{-7})$ 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 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 around 100 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.

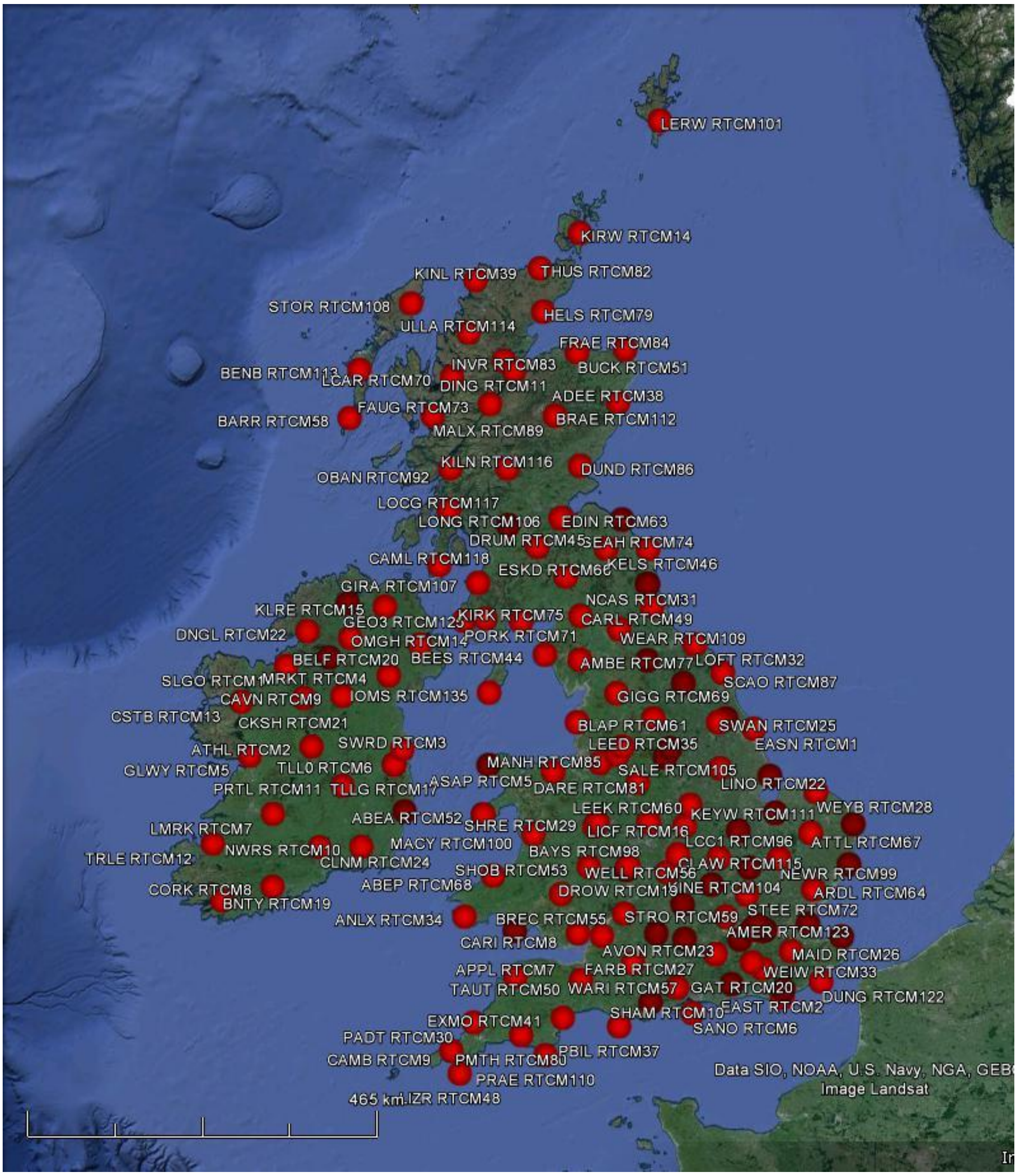

Figure 2-1: Leica SmartNet Network

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 mainly based on data from that site.

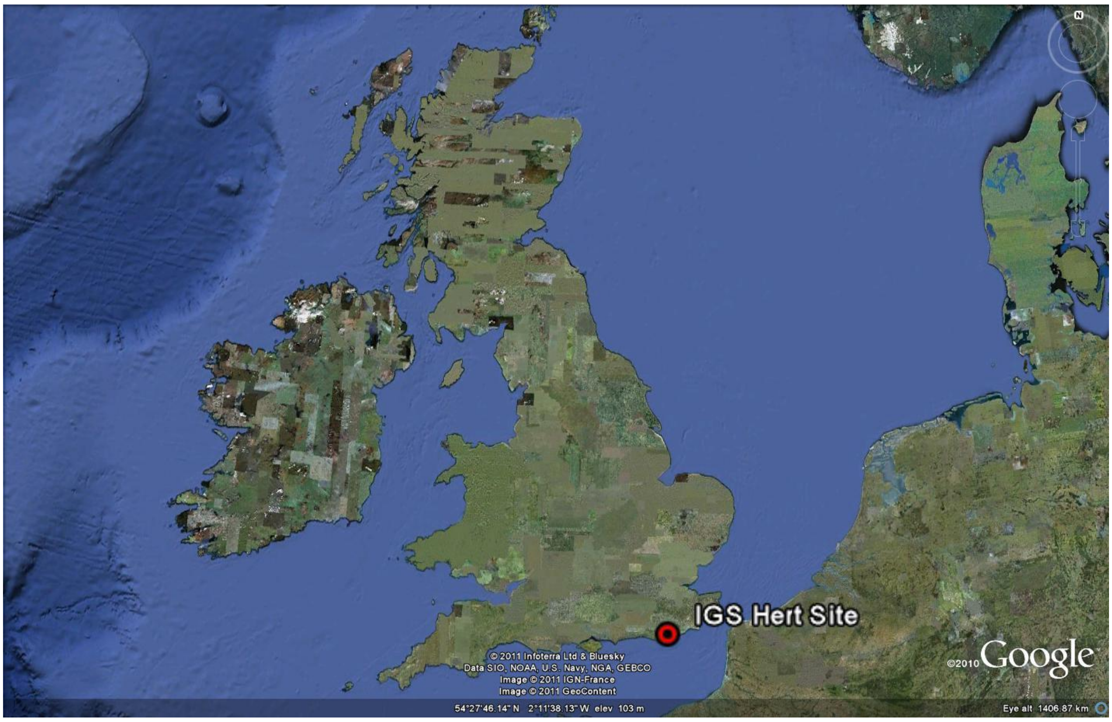

Figure 2-2: Location of IGS Hert Site

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].

2.4 Assumptions

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

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

Elevation, degrees	Error, metres
5	7.48

Elevation, degrees	Error, metres
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 5 degrees. The horizontal and vertical error distributions for the period July to September 2019 are shown in the following figures for fault-free solutions (i.e. no problems indicated). The samples shown in each figure are in error bins of 1cm and include position errors from all days during the monitoring period.

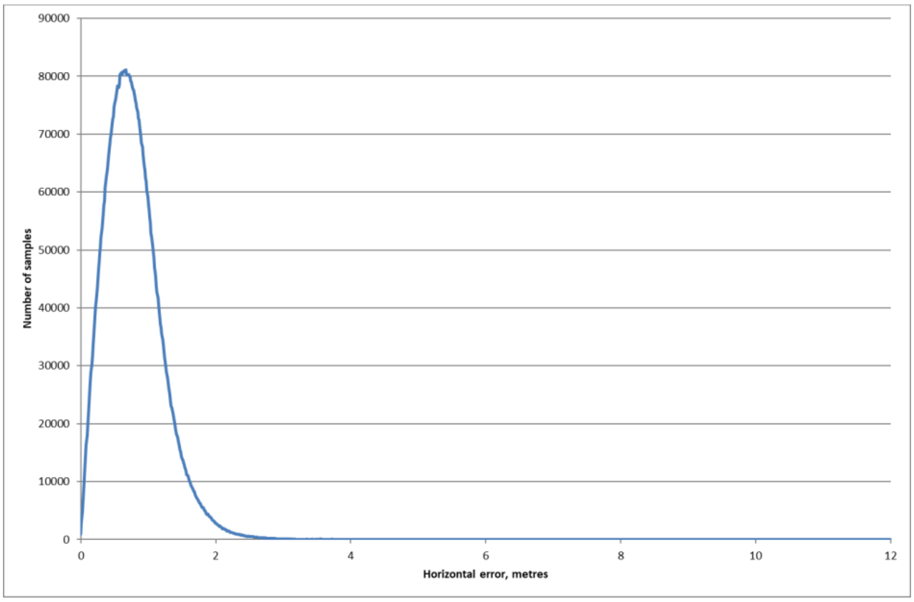

Figure 3-1: Horizontal Error Distribution for Monitoring Period

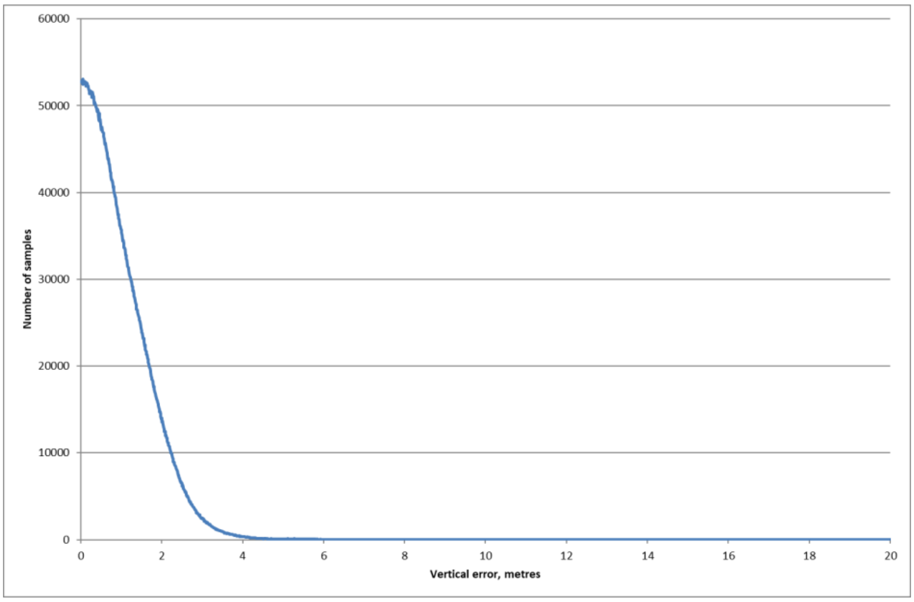

Figure 3-2: Vertical Error Distribution for Monitoring Period

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 3m and vertical error distribution above 4m are also shown.

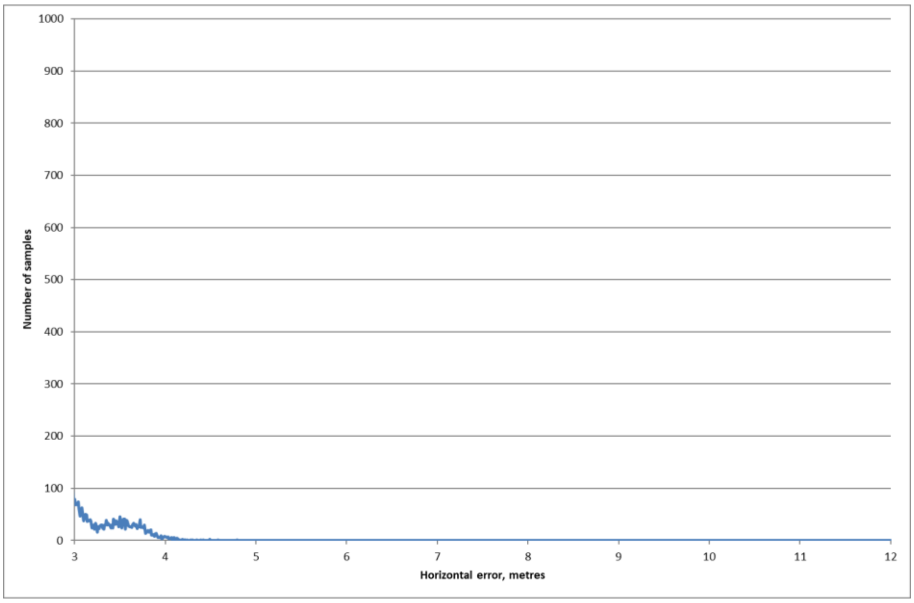

Figure 3-3: Horizontal Error Distribution above 3m for Monitoring Period

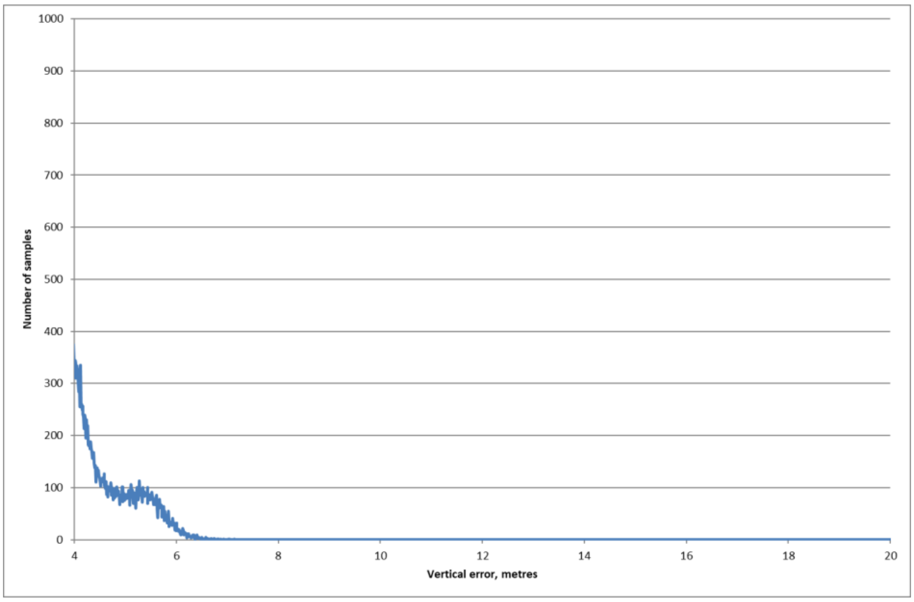

Figure 3-4: Vertical Error Distribution above 4m for Monitoring Period

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.

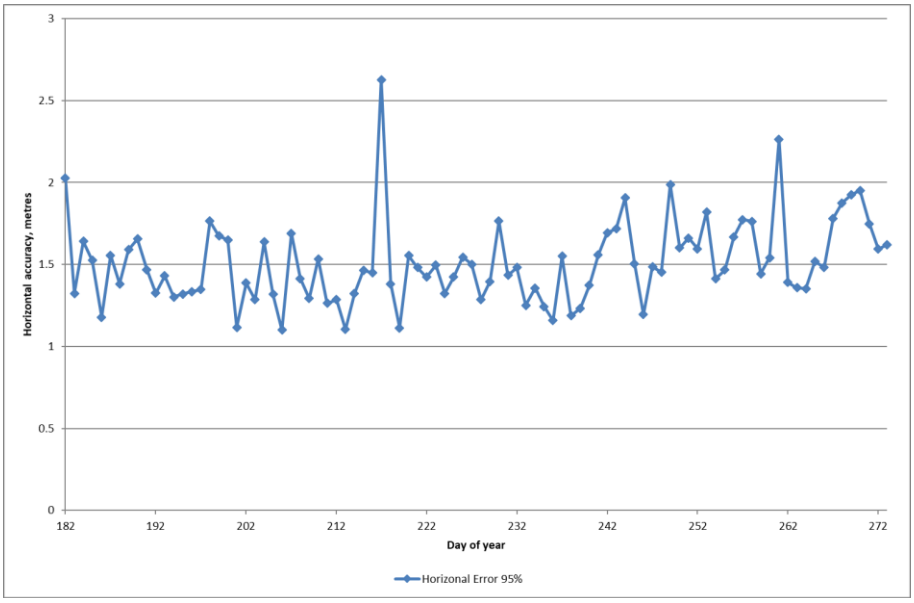

Figure 3-5: Horizontal Position Accuracy (95%) for Monitoring Period

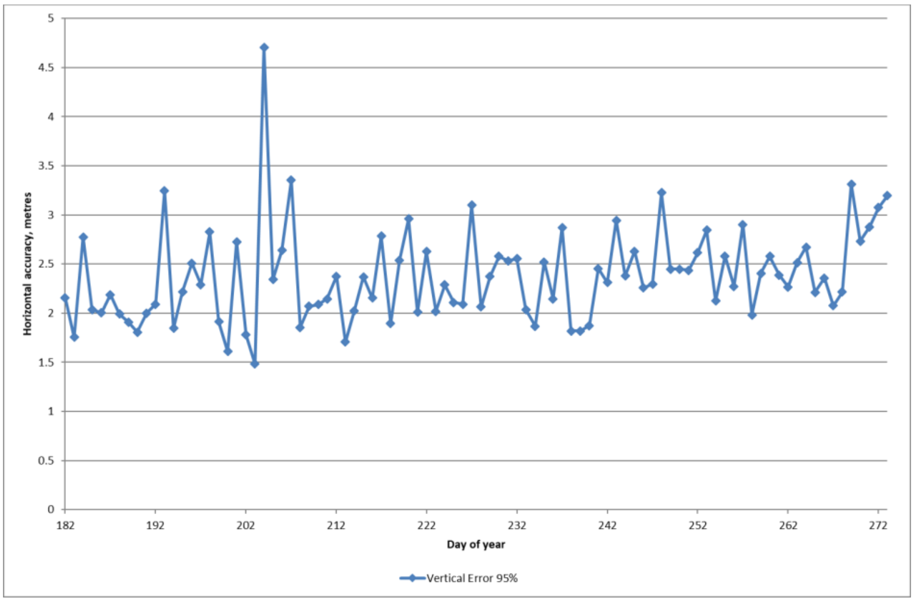

Figure 3-6: Vertical Position Accuracy (95%) for Monitoring Period

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 $1x10^{-7}$ per hour, the SiS probability of failure is determined as $1x10^{-4}$ 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 $2.78x10^{-8}$ per sample. Therefore, for the period analysed (i.e. 7948800 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 July to September 2019 were shown in section 3. It was seen that the horizontal errors were usually around 1-2m with a maximum value of <6m. 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 July to September 2019 the following potential failure events were observed.

Start Date	Start Time	Outage Duration (secs)	Reason for Outage	Comments
17/07/19	22:40:19	278	HPL > limit	This is due to an outage on PRN30 that was forecast by NANU 2019101. On the day before and after, PRN30 is in view at this time and there is no problem.
07/08/19	18:40:26	4	High position error (tens of km)	Receiver problem (see below)
29/08/19	19:46:04	249	HPL > limit	This is due to an outage on PRN02 that was forecast by NANU 2019136. On the day before and after, PRN02 is in view at this time and there is no problem.

Start Date	Start Time	Outage Duration (secs)	Reason for Outage	Comments
03/09/19	20:33:13	3	No solution (< 4 SVs)	Sudden drop in satellites tracked in obs file. Satellites are still tracked at other OS sites (e.g. LEED) so must be a local problem. As some low elevation satellites are still tracked it is unlikely to be interference. Possible receiver or data / comms issue?
03/09/19	20:45: 06	3	No solution (< 4 SVs)	Sudden drop in satellites tracked in obs file. Satellites are still tracked at other OS sites (e.g. LEED) so must be a local problem. As some low elevation satellites are still tracked it is unlikely to be interference. Possible receiver or data / comms issue?

Table 5-1: Summary of Outages during Monitoring Period

It can be seen from the table that there were 5 potential failure events during this period. Three of them seem to be due to local receiver problems and so are not counted as system failures. The other two are due to the system (low number satellites causing high HPL) but these were alerted ahead of time by NANU and so are not counted as failures. Therefore, the continuity for this period is 100%.

With regards the high position error on 07/08/19, the computed position error is tens of km due to erroneous range measurements on PRN09. This satellite was the subject of a NANU earlier in the day and so it was at first thought there could have been a problem related to this. However, these large errors are not seen at other sites at the same time. For example, LEEK starts providing measurements for PRN09 at 17:00 once it is healthy again and the position solution shows the measurements are fine. At LINO on the other hand, the receiver fails to track PRN09 until 18:40:26, more than 1.5 hrs after it was set healthy, and has very large errors in the measurements for 3 seconds before dropping it again. Only at 20:13:50 the receiver starts providing measurements again for PRN09 and this time they appear to be fine. In summary, the very large position errors for a few seconds on 07/08/09 are caused by erroneous range measurements on PRN09, but this appears to be due to a local receiver tracking problem rather than a system fault. In addition, as the range errors are so large they were easy to detect with a simple RAIM algorithm.

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 Table 5-1 it can be seen that during this period there were two system outages lasting for more than 10 seconds that were alerted by NANU but still count as outages for availability. Therefore, in this period the MMBO is (92 x 24) / 2 = 1104 hrs, and the MTTR is (278 + 249) / 2 = 263.5 seconds, or 0.073 hrs and therefore the availability was 99.9934%. This does fit in with the availability requirements specified in section 2.2.

7 CONCLUSIONS

The GPS performance has been assessed against the ICAO requirements for the period of July to September 2019.

- Accuracy
    - Horizontal accuracy checked against threshold of 220m.
    - 95% horizontal accuracy <3m on each day
    - Accuracy requirement is passed
- Integrity
    - Horizontal error checked against alert limit of 556m.
    - Maximum horizontal errors <6m
    - Integrity requirement is passed.
- Continuity
    - Results checked for outages (<5 satellites, position error > alert limit, protection level > alert limit).
    - Several potential outages identified, although most seem to be due to local/receiver errors and hence are not counted as an SIS outage.
    - Two are system issues but they are alerted through NANUs and therefore do not count as failures.
    - Continuity is 100% and therefore requirement is met.
- Availability
    - Results checked for outages (<5 satellites, position error > alert limit, protection level > alert limit).
    - Two system outages identified.
    - Availability is 99.9934% and therefore requirement is met for most of the range of values but not all.

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