

# Integrity and Continuity Analysis from GPS

## Annual Report

January – December 2009

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## 1 Introduction

The first GPS satellite was launched in 1978. This was an experimental satellite and a further 10 satellites of this type were launched until 1985. The first 'standard' satellite was launched in 1989 and by 1995 enough of these had been launched for the system to be declared operational. A Standard Positioning Service (SPS) specification document was published in 1996 to give users an idea of how well the system was expected to perform. For example, the horizontal position error during a 24-hour period was expected to be within 100m for at least 95% of the time as a result of performance degradation through Selective Availability (SA). SA was switched off in May 2000 and a new SPS specification document followed in 2001 [1]. According to this, during a 24-hour period the horizontal position error was not expected to exceed 36m for at least 95% of the time. Reflecting the user requirements and evolution of GPS, a new SPS specification was issued in September 2008 [2]. According to this, the horizontal position error is not expected to exceed 13m for at least 95% of the time.

Two issues which were not addressed directly in the SPS 2001 document, integrity and continuity, are now included in the new SPS 2008. However, the new stated performance levels are not suitable for aviation. These parameters (in addition to accuracy and availability) are highlighted below with respect to the quantities for Non-Precision Approach (NPA) as specified in the International Civil Aviation Organisation's (ICAO) Standards and Recommended Practices (SARPS) Annex 10 [3].

### 1.1 ICAO Standards and Recommended Practices

The ICAO Annex 10 Volume 1 Chapter 3 Section 3.7 details the ICAO SARPS for GNSS. 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 is a reproduction of the requirements specified for NPA together with a number of corresponding substantiations in the form of notes.

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

#### 1.1.1 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.”*

#### 1.1.2 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 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 NPA's 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.

### 1.1.3 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. Note that although operationally relevant, this approach can result in a relatively conservative measure. This report uses a variation of the above approach and one based on the ‘Period-of-Operation (PoP) concept’ as explained in Section 5.

### 1.1.4 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 modeling, 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. AMC-20-XX draft version 1.2 section 9.1.1 states that RAIM availability at the destination will be checked for the estimated time of arrival +/- 15 minutes during the pre-flight checks.

## **1.2 Study objectives and assumptions**

This study has the following four objectives based on GPS monitoring data for the period January-December 2009.

- Generate accuracy data and compare these to the requirement for NPA. This is performed by comparing positioning solutions from the monitoring receivers to the known coordinates of the antenna and generating the 95th percentile.
- Generate the integrity data based on the known position of the antenna. This process involves a comparison of the positioning solutions as determined from the measurements and the known position of the antenna. In the first instance a mapping of the ICAO requirements to the period under investigation is carried out to enable the determination of compliance with ICAO requirements.
- Generate continuity statistics including where gaps occur and the characteristics of each of the gaps, e.g. in terms of duration. The same approach as above on the mapping of continuity requirements to the sample domain is undertaken here also. Continuity risk is derived as a proportion of unsuccessful Periods-of-Operation (PoPs) to the total number of PoPs.
- Generate 'availability' statistics based on accuracy, integrity and continuity statistics.

This work is conducted under the following assumptions and limitations:

- monitoring at a static location in the East Midlands based on data collected using a geodetic (survey) receiver.
- the receiver used is fault-free receivers with a RAIM function that operates as designed, i.e. with a detection probability of 0.999.
- the use of satellites above an elevation cut-off (mask) angle of 10°

## **1.3 Structure of report**

Section 1 introduces the study including the relevant ICAO SARPS requirements and sets out the relevant objectives of the study and assumptions. Section 2 presents the main characteristics of the data including the types of receivers used, their capabilities and details the sample characteristics including antenna locations, quantity and frequency. Sections 3, 4, 5 and 6 present the methodologies and results of the data analysis organised in terms of accuracy, integrity, continuity and availability respectively. An analysis of unusual events identified in the sample is included in Appendix A.

## 1.4 Glossary and Abbreviations

|                     |   |
|---------------------|---|
| Almanac             | Broadcast satellite data giving approximate information about satellite positions with respect to time needed for the prediction of satellite visibility, geometry etc. |
| Accuracy            | See sections 1.1.1.   |
| Availability        | See sections 1.1.4.   |
| CAA                 | Civil Aviation Authority.   |
| Continuity          | See section 1.1.3.  |
| Broadcast Ephemeris | (plural ephemerides) a set of parameters which describe the location of satellites with respect to time, and which are transmitted (broadcasted) from the satellites    |
| Epoch               | A specific instant in time. The number of epochs in any given period depends on the measurement interval.   |
| Failure             | A failure is defined as an instant in time (depending on data characteristics) when the integrity requirement is not met.   |
| GNSS                | Global Navigation Satellite System.   |
| GPS                 | Global Positioning System.  |
| Integrity           | See section 1.1.2.  |
| Ionosphere          | Region of ionised particles in the earth's atmosphere which causes delays and refraction of GPS signals producing range errors.   |
| NPA                 | Non Precision Approach.   |
| Pseudorange         | A measure of the propagation time from the satellite to the receiver antenna, expressed as a distance.  |
| SIS                 | Signal-In-Space   |
| SNR                 | Signal to Noise Ratio.  |
| SPS                 | Standard Positioning Service  |
| TSO                 | Technical Standing Order.   |

## 2 Data Capture

### 2.1 Receiver

The receiver used is a Leica GRX1200 high performance GNSS reference receiver in conjunction with a multipath mitigating choke ring (LEIAT504) antenna. The receiver is configured to output raw (pseudorange and carrier phase) data measurements at 1Hz with a 10-degree elevation mask. Position solutions are calculated from the pseudorange measurements using special software developed at Imperial College London.

### 2.2 Data characteristics

The receiver used can output raw data in binary format via an RS-232 serial port. These data are subsequently recorded in the RINEX format file to facilitate processing with the Imperial Software. The characteristics of the relevant data used are given below.

- Raw code phase (pseudorange) measurements are a measure of the distance between each satellite and the receiver. This is used in part to calculate a position solution.
- Ephemeris information from each satellite enables the current position of the satellite to be computed at a specific time. This is used in part to calculate a position solution.
- Each GPS satellite also transmits an ionospheric model that allows some of the errors due to the ionosphere to be removed when calculating a single frequency position solution.

The receiver has been configured so that raw code phase (pseudorange) data is recorded every second. This means that there is a total of 86400 raw measurements in a 24-hour period. Satellite ephemeris information is recorded when needed. Typically one satellite ephemeris is valid for two hours and requires regular updates throughout the day. The GPS ionosphere model is recorded once every hour though in practice only one per day is needed.

In the period January-December 2009, there were 24 gaps where raw data were not recorded. Data from other stations (Zimmerwald in Switzerland and Hailsham in the UK) were subsequently processed to bridge the gaps. The details of the gaps and the analysis of their impact on the SIS monitoring are given in the appendix of the report.

### 3 Accuracy

Accuracy is defined here as a measure of the calculated position error between the position solution and the known location of the antenna at the 95<sup>th</sup> percentile. For the purpose of this analysis, all operational satellites above 10 degrees in elevation are used to compute a position solution.

The distribution of the position errors for the geodetic survey receiver is shown in Figures 1 and 2 for the period January-December 2009. Note that the vertical components are only included for completeness. The samples shown in each figure are in error bins of 1cm (i.e. for ease of representation, each sample represents a group of errors in the range of 10mm).

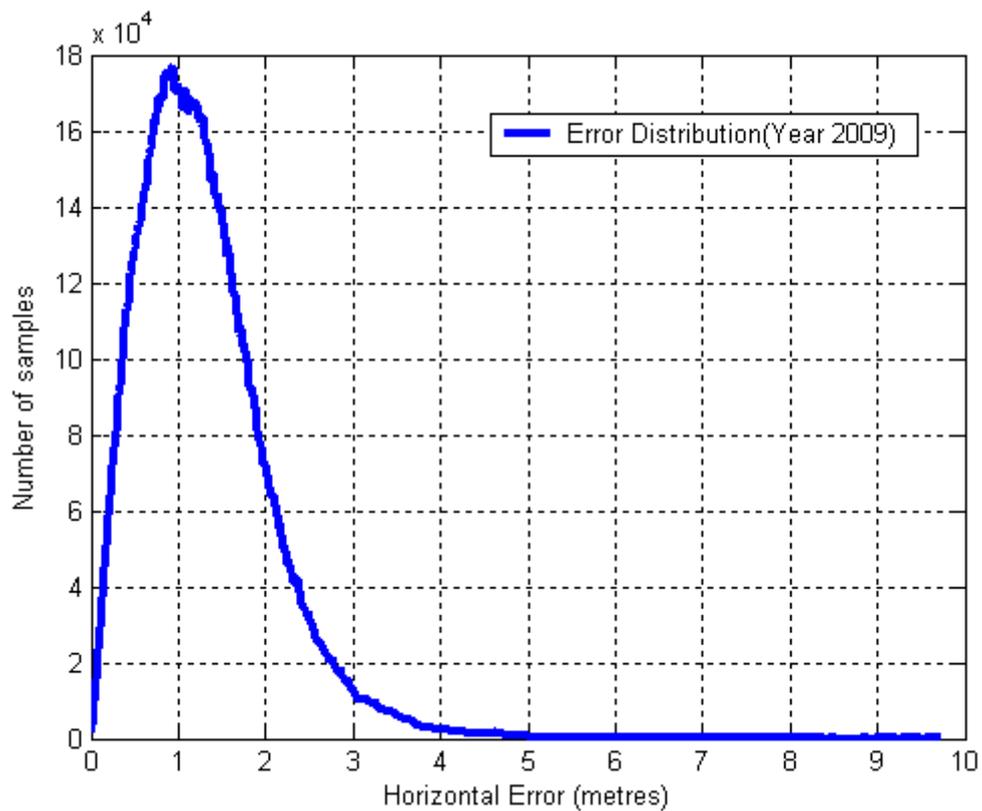
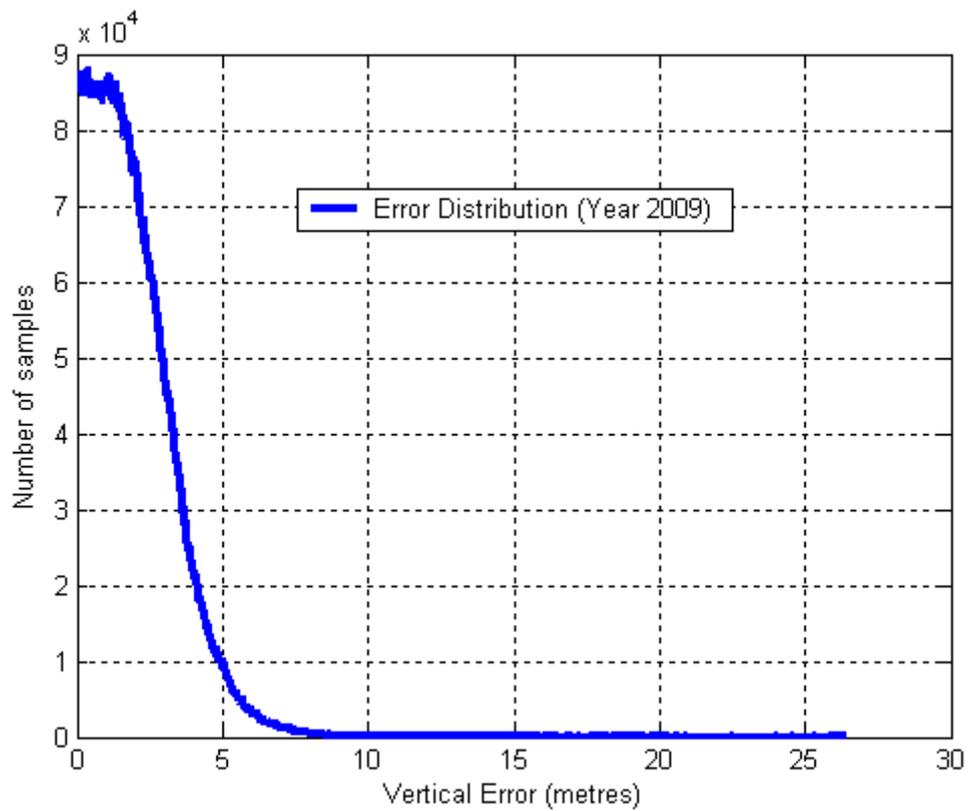


Figure 1 Horizontal Position Errors



**Figure 2 Vertical Position Errors**

To facilitate better comprehension of the anomalous excessive errors of interest to SIS monitoring, the horizontal accuracy statistics above 5m are shown in Figures 3 and the vertical accuracy statistics 8m are shown in Figures 4. The daily variations of the 95% horizontal and vertical positioning accuracies are then shown in Figures 5 and 6. It is clear from the results above that the accuracy requirement for Non Precision Approach (i.e. 220m, 95%) is satisfied during the period analysed.

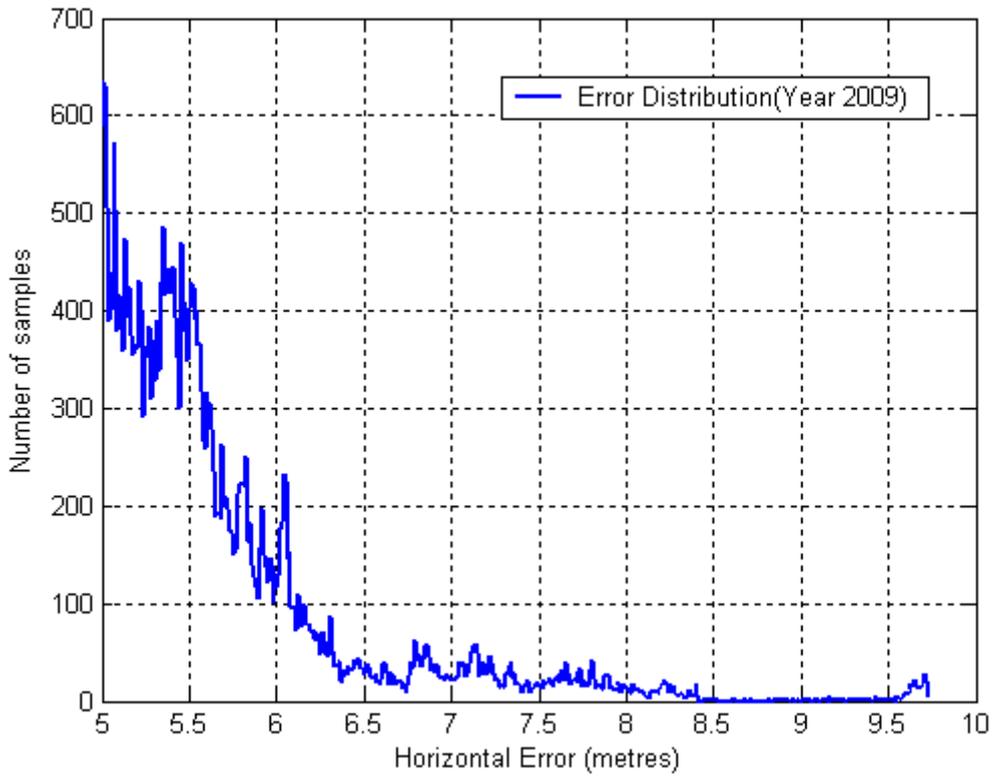


Figure 3 Horizontal Position Errors over 5 m

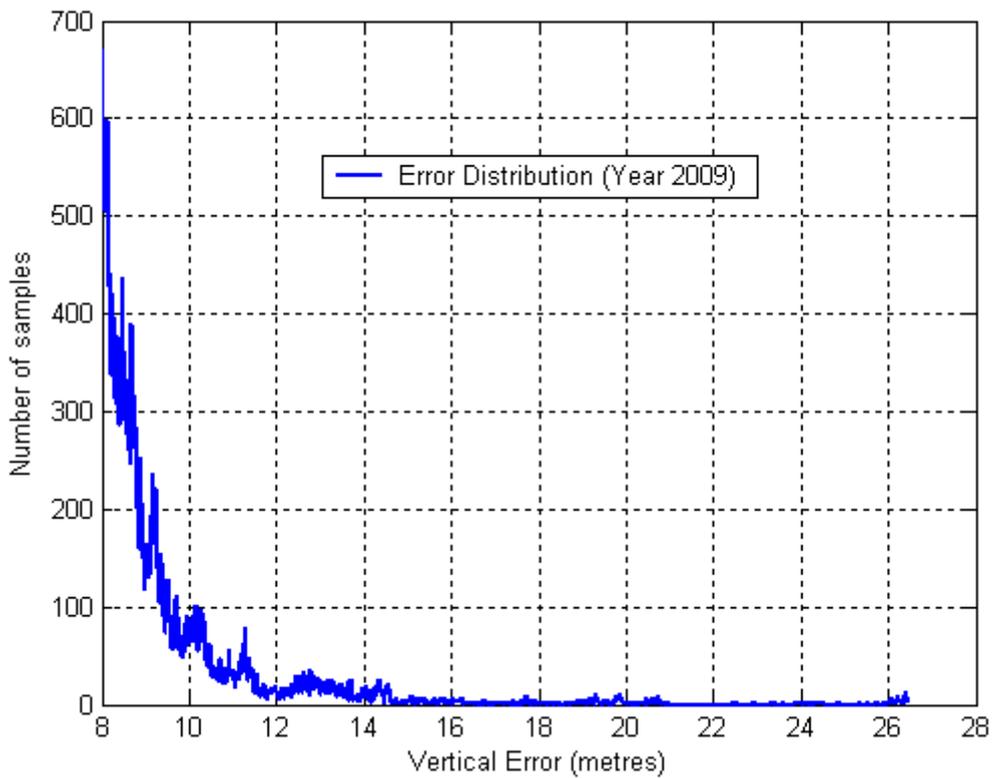


Figure 4 Vertical Position Errors over 8m

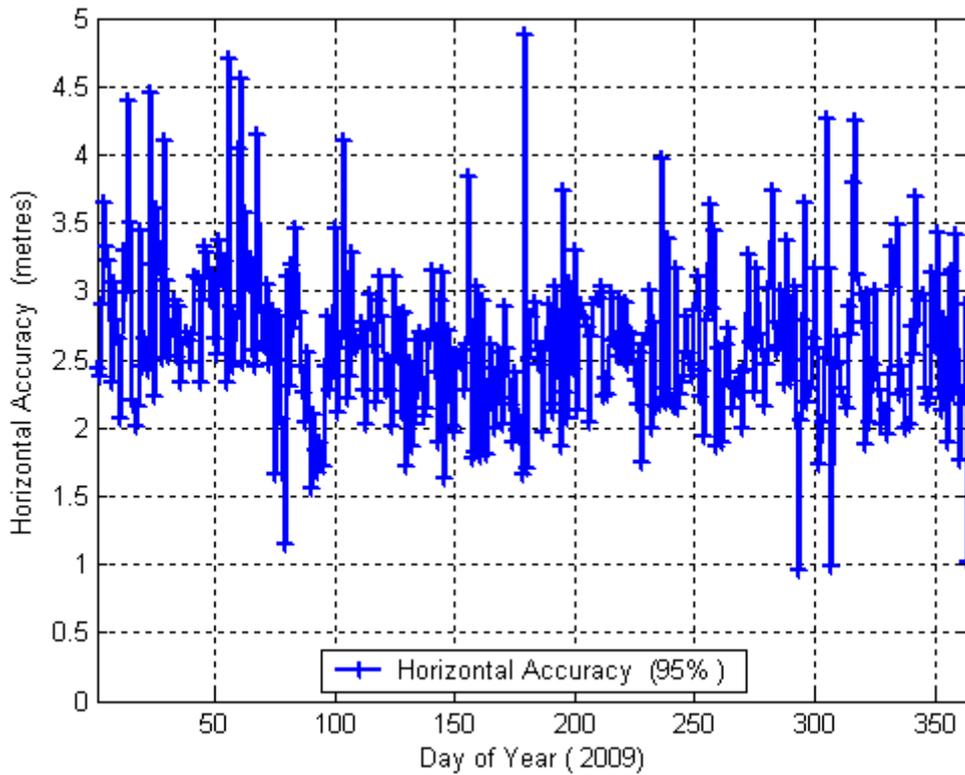


Figure 5 Daily variation in horizontal accuracy

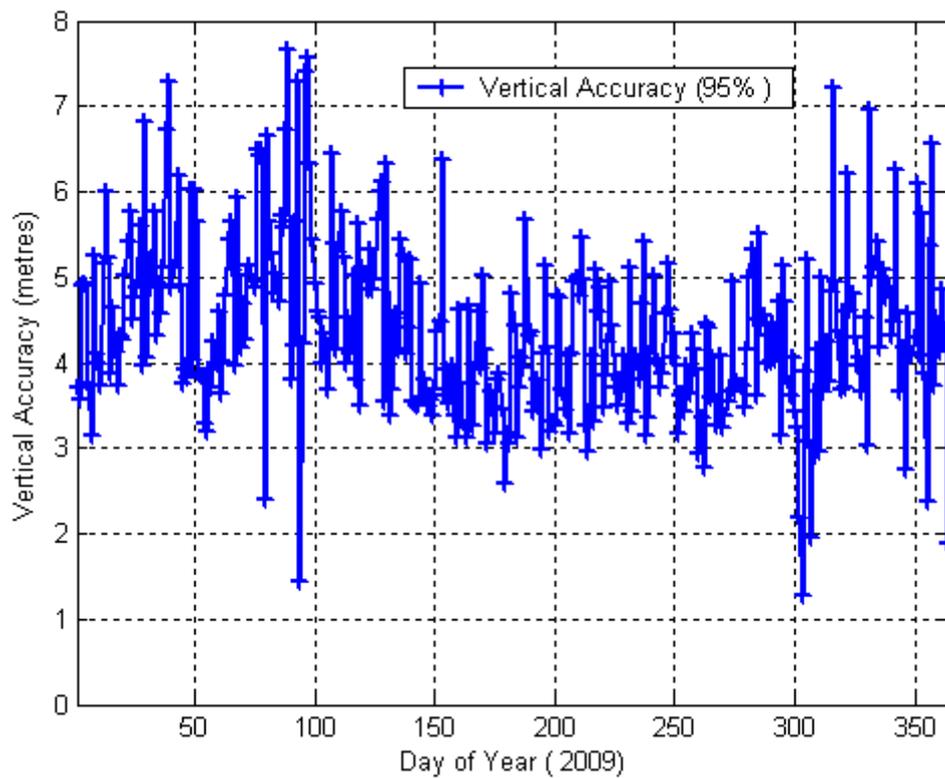


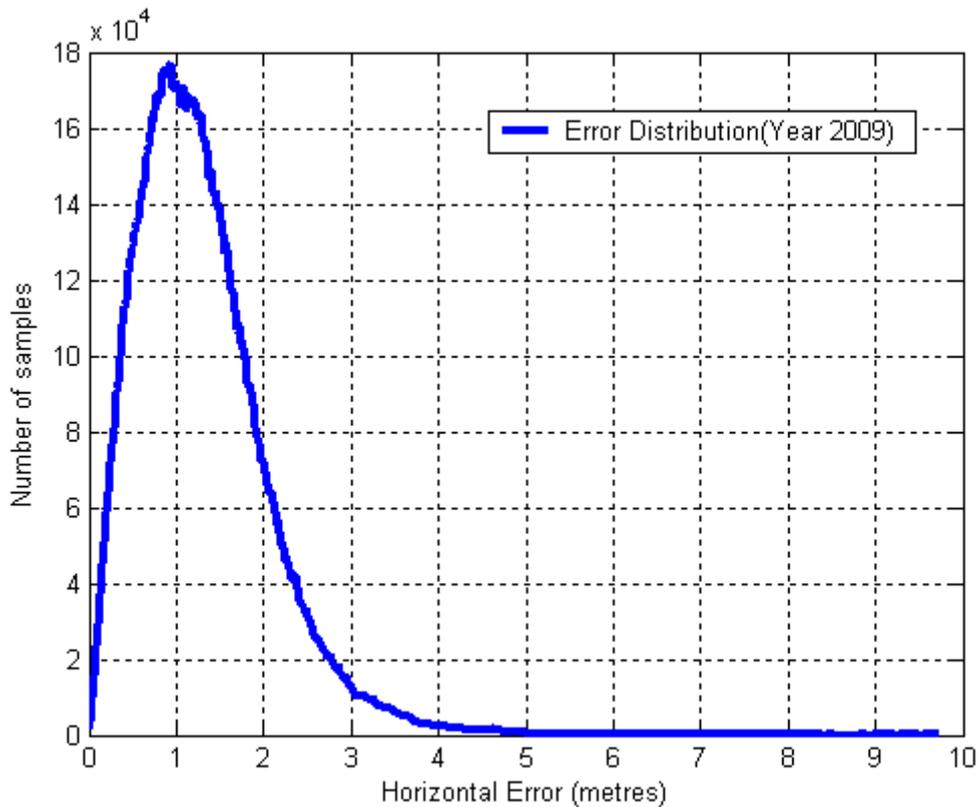
Figure 6 Daily variation in vertical accuracy

## 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 ( $P_{md}$ ) 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  $P_{md}$  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. 31536000 samples) the maximum allowable number of failures is 0.877.

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. 0.877). 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. It is nonetheless fairly effective in the case of NPA where the alert limit is relatively large.

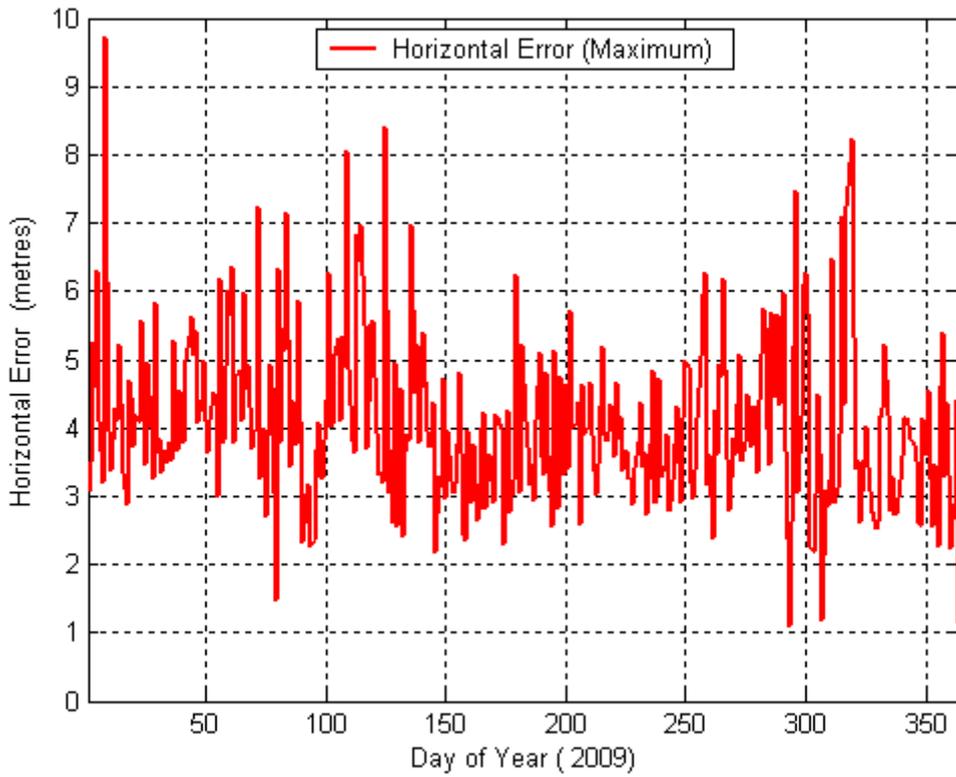
The distribution of horizontal position errors is shown in Figure 7 (the same as Figure 1 and repeated here for ease of reference).



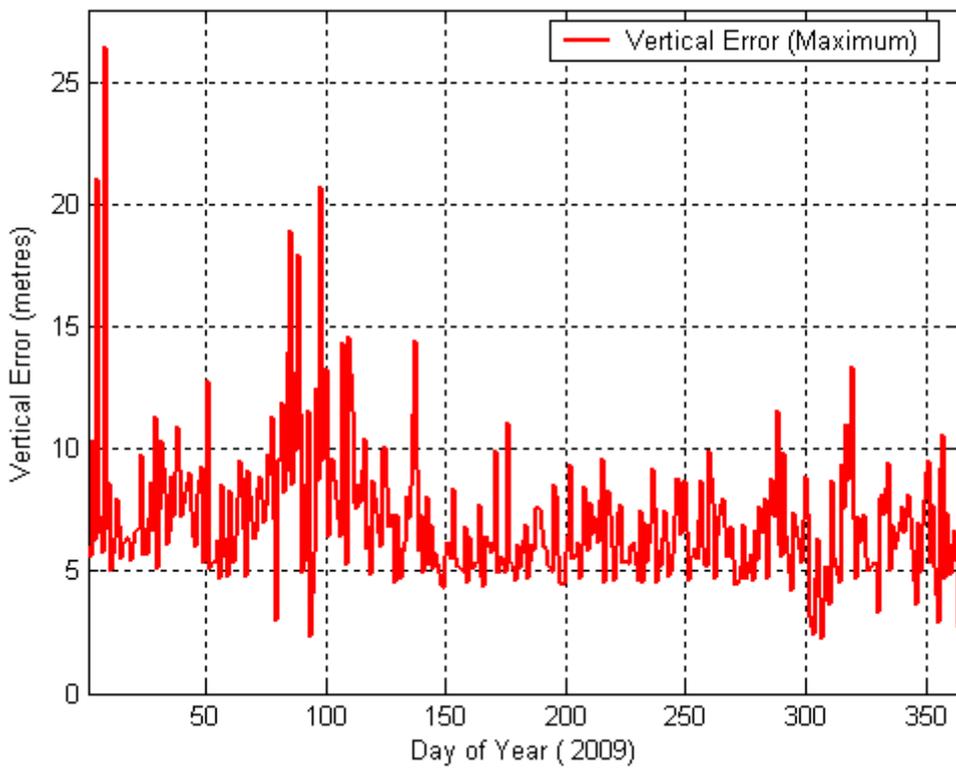
**Figure 7 Horizontal Position Errors**

The figures above show a large number of position errors that are close to zero. The remaining horizontal position errors are distributed in a normal way and the vast majority are less than 4m horizontal. The maximum single horizontal position error is less than 10m over the period. The integrity alarm limit is defined to be 556m and this has clearly been met throughout the period January-December 2009.

Since position errors around specified thresholds (in this case the alert limit) are of most concern in terms of detection, the worst-case (maximum) horizontal and vertical position errors for each day in the period January-December 2009 can be found in Figures 8 and 9 . It can be seen from Figure 8 that no horizontal position errors above are even close to 556m and therefore the integrity was 100% on each day in the period January-December 2009.

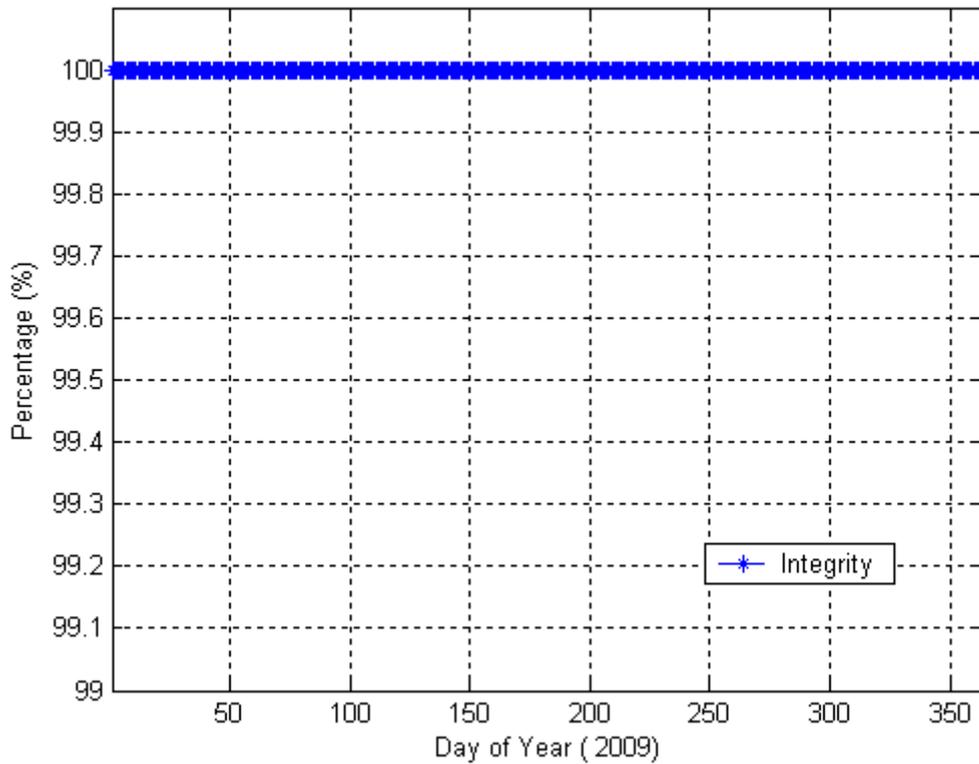


**Figure 8 Daily maximum horizontal errors**



**Figure 9 Daily maximum vertical errors**

In order to facilitate an understanding of daily variations, Figure 10 presents the integrity (measured in terms of the number of samples below the alert limit and expressed as a percentage) for each day over the period analysed. It can be seen that the integrity performance was at the 100% level on each day in the period January-December 2009.



**Figure 10 Integrity performances (percentage)**

## 5 Continuity

Two approaches have been used to quantify system performance with respect to continuity. The first is referred to as the PoP concept and the second referred to as the simple count method.

### **The PoP concept**

From the definition of continuity, a number of parameters need to be specified. These are continuity risk and Period-of-Operation (PoP) for NPA. The duration of a typical PoP is taken in this report as the average for six relevant airports (Blackpool, Durham, Exeter, Gloucester, Inverness and Shoreham). Two values are determined one for the basic approach and the other including missed approach. The corresponding PoP values are 3.75 minutes (225 seconds) and 12.33 minutes (740 seconds) respectively. Since monitoring is carried out at a static location, over the period January to December 2009, there were a total of 140160 PoPs in the basic approach mode and 42616 POPs when missed approaches are included. For example, taking a continuity risk of  $1 \times 10^{-4}$  per hour (note that this is to be specified by the service providing according section 1.1), the risk per PoP in the basic approach mode is  $6.25 \times 10^{-6}$ . This results in the maximum number of allowed interrupted PoPs of 0.876. The corresponding figures for including missed approach are  $2.056 \times 10^{-5}$  and 0.876 respectively. This maximum allowable interruptions are then the basis for assessment of compliance with ICAO requirements.

Based on the accuracy and integrity results and the analysis presented in Appendix A and Appendix B, it is clear that there were no interruptions during the period analysed (i.e. continuity of service with respect to SiS was at the 100% level).

### **The simple count method**

In this approach the total number of independent samples is determined (see Section 4) and the following parameters counted: the number of samples that exceed the alert limit and the number of samples when RAIM is unavailable. Note that ideally the number of false alerts should also be included if the system performance assessment includes that of the receiver. The sum of these is divided by the total number of samples and expressed as a probability per hour.

For the period analysed, there were no samples that exceeded the alert limit and no cases of RAIM unavailability. For this reason the continuity risk was zero.

In order to facilitate an understanding of daily variations, Figure 11 presents the continuity (measured in terms of the number of samples below the alert limit and expressed as a percentage) for each day over the period analysed. It can be seen that the continuity performance was at the 100% level on each day in the period January-December 2009.

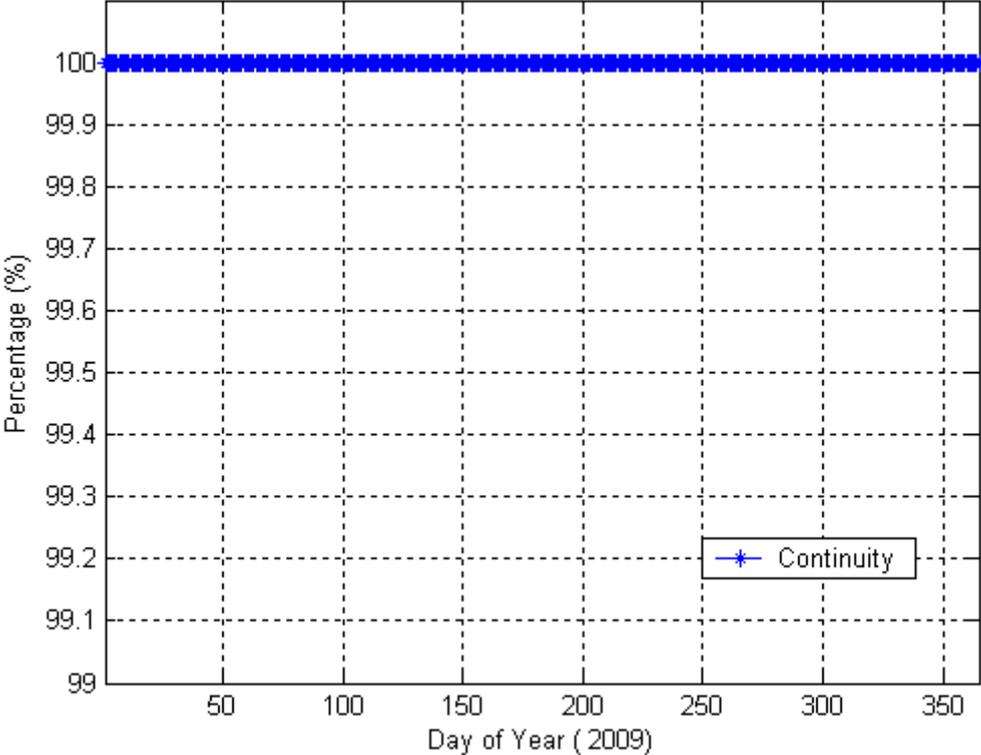
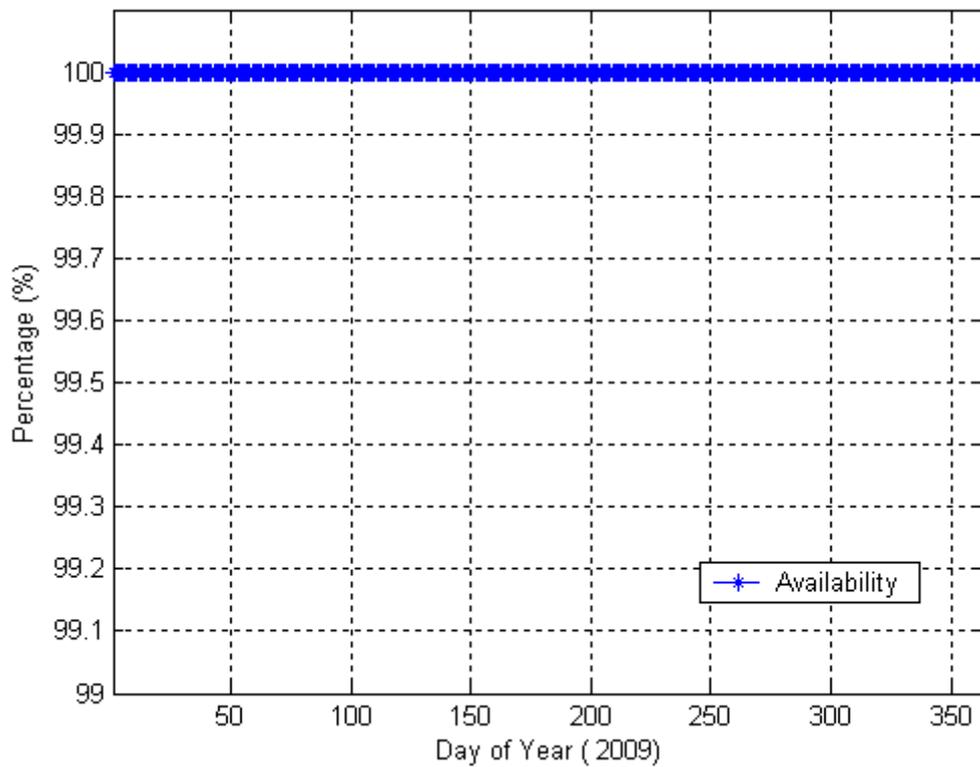


Figure 11 Continuity performance (percentage)

## 6 Availability

Based on accuracy, integrity and continuity results, it is clear that the SiS availability during the period analysed was at the 100% level. The availability performance is shown in Figure 12 for each day in the period January-December 2009.



**Figure 12 Availability performance (percentage)**

## 7 References

1. Department of Defence (2001), Global Positioning System Standard Positioning Service Performance Standard, USA.
2. Department of Defence (2008), Global Positioning System Standard Positioning Service Performance Standard, USA.
3. ICAO SARPS (2006), Annex 10: International Standards and Recommended Practices: Aeronautical Telecommunications, Volume 1, Edition 6, International Civil Aviation Organisation.
4. Integrity and Continuity Analysis from GPS, Quarterly report to CAA (2009 Quarter 1)
5. Integrity and Continuity Analysis from GPS, Quarterly report to CAA (2009 Quarter 2)
6. Integrity and Continuity Analysis from GPS, Quarterly report to CAA (2009 Quarter 3)
7. Integrity and Continuity Analysis from GPS, Quarterly report to CAA (2009 Quarter 4)

## Appendix A Bridging the data gaps

This section investigates any anomalies or unusual events in the raw data captured by the survey receiver. In 2009, there were 24 gaps when raw data were not recorded. The details of these gaps were given in quarterly reports.

Among the gaps, the very short period ones had repeatedly occurred at the East Midlands monitoring receiver but did not occur at the other IGS stations including Zimmerwald in Switzerland and Hailsham in the UK, thus pointing to a local problem with receiver or data recording. These gaps were likely to be due to receiver problems including software bug, signal acquisition and computer interfacing. The remaining long period gaps were due to major receiver data recording system failures and at some point in the year, a change of location (site) of the East Midlands Station.

Data from an external receiver were processed to find if it was recording data during these gaps. The IGS stations Hailsham and Zimmerwald were found to have recorded reliable data and were therefore, used to bridge the gaps in the data from the East Midlands station. A combination of 1 and 30 second data sets (the latter for 3 days in 2009 due to unavailability of 1Hz data) were downloaded from the IGS website (<http://igsceb.jpl.nasa.gov>). The relevant horizontal and vertical position errors have been incorporated in the results from the East Midlands Station to generate the overall performance statistics.

In conclusion the continuity of the GPS SIS in 2009 was at the 100% though local issues arose with the East Midlands survey grade receiver.