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GPS Integrity and Potential Impact on Aviation Safety

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GPS Integrity and Potential Impact on Aviation Safety

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Executive Summary

This report is the culmination of a study of the level of safety as measured by integrity (i.e. trustworthiness), afforded by the Global Positioning System (GPS) as a source of navigation data for civil aircraft. The study was carried out by IC Consultants Limited on behalf of the Safety Regulation Group (SRG) of the Civil Aviation Authority (CAA). It is a contribution to a long-term programme by the CAA on hazard analysis of navigation systems for civil aviation. Such a programme has been necessitated by the requirement of the CAA to ensure that the integration of GPS into traditional and novel safety related applications is done without compromising safety. The study had two main objectives. The first was to provide concise definitions of integrity within the contexts of an air traffic service (ATS) and the required navigation performance (RNP) for civil aviation. The second was to investigate potential cases of non-integrity (i.e. failures), which could result in safety risks, their causes and mitigation techniques.

Integrity of any system refers (just as it does to a person) to trustworthiness and is an important safety parameter. It should be noted that the scope of this study was defined to cover just one element of an air traffic service. A generic ATS consists of 3 main components, human (e.g. air traffic controllers), infrastructure (e.g. CNS/ATM technologies) and the necessary interfaces (e.g. human/human, human/infrastructure, ATS/aircraft, ATS/ATS). Hence in order to ensure a high level of safety all the components of an ATS must have the highest level of integrity. Furthermore, the overall safety of an aircraft does not only depend on the level of safety afforded by the ATS but also the aircraft itself including equipment on board and pilots.

The performance requirements expected of a global navigation satellite system (GNSS) such as GPS, are specified for all phases of flight by the International Civil Aviation Organisation (ICAO) in the Standards and Recommended Practices (SARPs) for civil aviation. The requirements are in terms of the four parameters of **accuracy**, **integrity, continuity and availability**. Accuracy is defined as the degree of conformance of an estimated or measured position at a given time to a defined reference value. Integrity relates to the level of trust that can be placed in the information provided by the navigation system. It includes the ability of the navigation system to provide timely and valid warnings to users when the system must not be used for the intended operation or phase of flight. Specifically, a navigation system is required to deliver a warning (**an alert**) of any malfunction (as a result of a set **alert limit** being exceeded) to users within a given period of time (**time-to-alert**). Continuity of a navigation system is its capability to perform its function without non-scheduled interruptions during the intended period of operation (POP). Availability is defined as the percentage of time during which the service is available (i.e. reliable information is presented to the crew, autopilot or other system managing the flight of the aircraft) for use taking into account all the outages whatever their origins. The service is available if accuracy, integrity and continuity requirements are satisfied.

The adoption of GPS for civil air navigation for any phase of flight must therefore depend on whether it satisfies the required navigation performance for civil aviation as defined by the ICAO. With respect to integrity (as the parameter most directly related to safety) a potential safety hazard (i.e. loss of integrity) can happen in one of two ways. Either an unsafe condition is not detected or it is detected but the alert is not received by the pilot within the required time-to-alert. The important question here with respect to GPS is whether there are potential situations that could result in unsafe operational conditions, and if so how would GPS deal with them, and whether this satisfies the required navigation performance.

GPS is a complex system, based on data messages transmitted from a constellation of satellites. There is a potential for failure at any one of a number of stages, from the production of the data messages and their upload to the GPS satellites, to their transmission, reception and processing within the user receiving equipment. This study has identified (and attempted to quantify the impact in some cases) a number of things that have and could go wrong (and result in loss of integrity). The information has been determined from various sources and organised into three distinct levels: system, operational and user.

- **System level failures:** These are failures that could occur within the GPS operational control system in the ground segment and within the space segment. Example sources of failure include erroneous clock data, incorrect modelling and malfunction in Master Control Station (MCS), and satellite related instabilities (satellite payload, satellite orbits, space vehicle control, radio frequency).
- **Operational level failures:** These are failures that could occur as a result of factors associated with the operational environment. Example sources of failure include intended signal interference, unintended signal interference and sudden changes in the signal propagation properties within the atmosphere.
- **User and User Equipment level failures:** These are failures that could be induced by the receiving equipment and the user. Example sources of receiver-induced failures include those related to hardware and software.

The study has determined that the current GPS architecture provides a certain level of protection against anomalies and failures at two levels, system and user. The first is by relying on satellite self-checks and monitoring by the US DoD Operational Control Segment (OCS) Master Control Station (MCS). The second is through signal assessment by users. Thus GPS has both integral and independent mechanisms for integrity monitoring. User level integrity monitoring uses a method applied within the user receiver to enable it to independently or autonomously establish system integrity. Receiver Autonomous Integrity Monitoring (RAIM) attempts to address two main concerns. The first is the existence of a bad measurement. The second is the identification of the affected satellite. These processes require redundant measurements.

A careful analysis of the system level integrity monitoring offered by GPS has revealed that although the current GPS control segment and the satellites themselves provide a reasonable level of integrity, anomalies could go undetected for too long a period exceeding the time-to-alert requirements (note that this requirement for en-route and oceanic phases of flight are 2 minutes and 1 minute respectively). It typically takes the MCS 5 to 15 minutes to remove a satellite with a detected anomaly from service. Furthermore, if a satellite is not in the view of one of the ground stations (the ground stations provide only 92 percent tracking coverage), an anomaly could go undetected for a longer period of time before the MCS can realise the situation and take remedial action. Hence, system level integrity monitoring is not adequate for aviation. This point is emphasised by the fact that there is no specification for the expected integrity performance given in the GPS Standard Positioning Service (SPS) Performance Standard document. In fact, the document states that GPS SPS performance is not currently monitored in real time.

With respect to user level integrity monitoring through RAIM, the study has quantified the capability of the GPS constellation to provide the conditions to perform a RAIM computation (i.e. RAIM availability). The results for non-precision and precision approaches (and other phases of flight with more strict RNP requirements) show that that user level integrity monitoring through RAIM is not sufficient to meet the RNP.

As neither of the two approaches to the monitoring of GPS integrity is adequate, GPS would have to either be modernised or augmented to satisfy the civil aviation integrity requirements.

On the issue of modernisation, the study has found evidence to the fact that there are plans to modernise GPS under the GPS III programme in order to provide improved capabilities to fully support safety critical applications such as aviation. The first GPS III satellite is to be launched in 2009 with an eventual 30-satellite constellation. The programme is currently in the requirements definition phase and is expected to be fully operational in 2020.

In the short to medium term ground-based augmentation systems (GBAS), aircraft-based augmentation systems (ABAS), space-based augmentation systems (SBAS) and augmentation with stand-alone GNSS such as Galileo offer the possibility to achieve the RNP. This study has shown that GPS augmented with Galileo offers a user level monitoring capability through RAIM good enough to satisfy the integrity requirements for en-route to precision approach phases of flight. The adoption of GBAS (e.g. local area augmentation), ABAS (e.g. integrated GPS /INS) and SBAS (e.g. wide area augmentation through EGNOS and WAAS) should enable the RNP to be achieved for all phases of flight. Further research and development is still required before these systems could be certified for civil aviation.

Regulatory process

An important objective of the CAA regulatory process should be to put in place a method to deal with certification requests for systems and process to be used in safety critical applications. Such a process requires a credible qualitative and quantitative verification plan and methodology to independently assess whether proposed systems and services perform as designed and within the operational performance requirements. In order for this to be done, the ATS requirements and architecture should be understood to the lowest (elemental) level together with the corresponding failure modes and rates. From this, a hazard analysis could be carried out for the entire service. This study has been a contribution to this with respect to the navigation element.

With respect to GPS, the study has shown that GPS is susceptible to different types of failures with potential impacts on safety. It is important that further analysis of the failure modes and rates (probabilities) and their corresponding impact on safety and performance requirements are carried out. This would involve the following steps.

a) Consolidation and bounding of possible system and operational failure modes including probabilities of failure

b) Consolidation and bounding of the effects of different user equipment on incident signal failures and also user equipment performance levels and failures.

c) Definition of the necessary test and simulation parameters, e.g. area of operation.

d) Execution of simulations to determine if the requirements of the phase of flight in question can be achieved based on simulated range measurements as opposed to availability analysis.

e) Determination of mitigation strategies and repetition of steps a) to d) for those strategies involving augmentation with other sensors and systems.

The results of the above exercise should form an essential input into the specification of a verification process for GPS-based navigation systems. Similar exercises should then be carried out for remaining elements of ATS in order that an overall safety case can be determined.

GPS Integrity and Potential Impact on Aviation Safety

1 Introduction

This report has been prepared by IC Consultants Limited for the Safety Regulation Group (SRG) of the Civil Aviation Authority (CAA) and contains the results of a study of the level of safety afforded by the Global Positioning System (GPS) as a source of navigation data for civil aviation. The report is a contribution to a long-term programme by the CAA on hazard analysis of navigation systems for civil aviation.

1.1 Background to the study

The demand for air travel worldwide continues to grow at a rapid rate, especially in Europe and the United States. In Europe, the demand exceeded predictions with a real annual growth of 7.1% in the period 1985 to 1990 against a prediction of 2.4% (Eurocontrol, 1987). This is expected to double by the year 2010. The demand has not been matched by availability of capacity. In 1989, the annual cost due to inefficiency in the provision of air traffic services was estimated at 5 Billion US Dollars (Lange, 1989) attributed mainly to non-optimal route structures and reduced productivity of controllers as a result of inefficient equipment. Note that whilst the demand figures have been revised downwards since the unfortunate incidents of 11 September 2001, the belief in the industry is that demand will rise again to the original predicted levels within a few years.

In the early 1980's, the International Civil Aviation Organisation (ICAO) recognised that the traditional air traffic control (ATC) systems would not cope with the growth in demand for capacity. As a result it established the Special Committee on Future Air Navigation Service (FANS) to study, identify and assess the new technologies as well as to make recommendations for the future development of navigation systems for civil aviation. This led to development of a satellite-based system concept to meet the future civil aviation requirements for communication, navigation, and surveillance/air traffic management (CNS/ATM). The concept involves the application of state-of-the art technologies in satellites and computers, data links and advanced flight deck avionics to cope with air traffic service requirements. This should remove the need for relatively expensive ground-based equipment, which use line-of-sight technology and has inherent limitations. It is expected to produce benefits in efficiency, economy and safety. More importantly it is expected to be an integrated global system with consequential changes to the way air traffic services are organised and operated.

The navigation function of CNS/ATM is to be supported by the use of signals from global satellite navigation systems (GNSS). This is instead of the ground-based beacons and navigation aids currently in use. The space-based navigation system must provide the so-called required navigation performance (RNP) for civil aviation, specified in terms of the four parameters of accuracy, integrity, continuity of service and availability. Of the RNP parameters, integrity (i.e. the trust which can be placed in the information supplied by the navigation system) is the one that relates most directly to safety, and is therefore a crucial element, particularly for safety critical applications such as civil aviation. The RNP for all phases of flight is specified in the ICAO Standards and Recommended Practices (SARPs) for civil aviation (ICAO, 2000).

1.2 Context of the study

The main GNSS currently in use for some navigation applications is the US Global Positioning System (GPS). The CAA is required to ensure that the integration of GPS into traditional and novel safety related applications is done without compromising safety. An important part of this is the need to ensure that safety issues both in terms of requirements and performance limitations associated with the use of GPS for civil air navigation are clearly understood by current and potential users. Therefore, on grounds of safety, it is necessary to create a sound and robust paper on integrity (as the navigation performance parameter most directly related to safety) on which to base UK policy and to act as a foundation for further research within the Safety Regulations Group (SRG) of the CAA. This report attempts to fulfil this requirement.

The report is intended for dissemination to all levels of industry and Government Agencies (GA) with the aim of appraising industry of all integrity issues with a clear and indisputable rationale. Hence, it adopts a neutral stance, discussing industry solutions to integrity but not promoting any particular solution.

1.3 Objectives of the study

The main objectives of the study are given below.

- Define integrity in the context of the RNP for civil aviation.
- List the potential causes of non-integrity (i.e. failure modes) and analyse the level of safety afforded by GPS.
- Identify and analyse the GPS integrity augmentation mechanisms.

1.4 Structure of report

The report contains the following.

- Section 1, this introduction, gives the background to the study, its context and objectives, and the structure of the report.
- Section 2 presents the definition of integrity in the context of the required navigation performance concept.
- Section 3 presents an overview of integrity assurance (monitoring) methods for satellite navigation systems.
- Section 4 looks at the current status of GPS, lists the failure modes that could result in the loss of integrity and discusses its system and user level integrity monitoring capability.
- Section 5 analyses the future status of GPS based on ongoing and proposed modernisation initiatives and the corresponding integrity monitoring capability both at system and user levels.
- Section 6 identifies and analyses the options available for augmenting GPS to improve integrity.
- Section 7 concludes the report summarising the key findings and identifying the critical issues that require further study.

2 Definition of Integrity

This Section provides a clear definition of the term **integrity** both in general and within the context of the required navigation performance (RNP) for civil aviation. Distinction is made between integrity performance required of a navigation system such as GPS and a total air traffic service (ATS).

2.1 General definition

Several English dictionaries give the definition for the term integrity as quality expressed in terms of several key words including uprightness, honesty, sincerity, veracity and trustworthiness. The integrity of any system therefore, refers (just as it does to a person) to a measure of quality expressed in terms of these keywords. This measure is important in ensuring the safety of any system. Hence, integrity is a key safety parameter.

2.2 Air Traffic Service and Integrity

A good air traffic service (ATS) should provide a safe, efficient and cost effective management of air traffic in a given airspace. Such a service generically consists of 3 main components, human (e.g. air traffic controllers), infrastructure (e.g. CNS/ATM technologies) and the necessary interfaces (e.g. human/human, human/infrastructure, ATS/aircraft, ATS/ATS). It follows from the above definition of integrity that in order to ensure the highest level of safety, all the components of an ATS must have the highest level of integrity. It should be noted also that the overall safety of an aircraft does not only depend on the level of safety afforded by the ATS but also the aircraft itself in terms of the equipment on board and the pilots. The study presented here looks at just one element of an ATS, i.e. navigation, and particularly the level of safety afforded by GPS as a source of navigation data.

2.3 Required Navigation Performance (RNP) and GNSS Performance Requirements

The required navigation performance (RNP) is a concept endorsed by the International Civil Aviation Organisation (ICAO), and is a statement of the navigation performance necessary for operation within a defined airspace. RNP is specified for the different phases of flight or RNP types in terms of the four parameters of **accuracy, integrity, continuity** and **availability**. It is important to note that the definition of RNP is for the total system including navigation signal-in-space (SIS), the airborne equipment, and the ability of the aircraft to fly the desired trajectory.

As this paper is concerned with the level of integrity afforded by GPS, and assuming that the airborne receiver is fault free (at the very least meeting the minimum operational performance standards for airborne equipment to be used with GPS), it is the navigation signal-in-space requirements that are important in assessing the capability of GPS. A detailed explanation of the concept of RNP and the quantification of the parameters can be found in ICAO (1999; 2000). The performance requirements expected of a global navigation satellite system such as GPS expressed in terms of the RNP parameters of accuracy, integrity, continuity and availability are given in Table 1 (ICAO, 2000; Volpe, 2001; RTCA, 1998; US DoD, 2000).

In order to facilitate the understanding of the contents of Table 1, a brief explanation for each of the performance parameters is given below.

2.3.1 Accuracy

This is the most obvious navigation system requirement. Accuracy is defined as the degree of conformance of an estimated or measured position at a given time to a defined reference value. Ideally, this reference value should be a true value, if known, or some agreed-upon standard value. The accuracy of a clock, for example, is determined by how well it keeps time compared with a standard clock, such as an atomic clock maintained by a national timing laboratory. In terms of satellite positioning, a reference value might be the published coordinates of a geodetic reference mark.

Accuracy should not be confused with precision, which denotes a measurement quality that describes how well repeated measurements agree with themselves rather than with a reference value. In other words it is determined by the scatter or dispersion of measurements. There are various ways of quantifying precision, including standard deviation, variance, range and confidence, and probability intervals.

The accuracy requirement of a GNSS navigation system is specified at the 95 percentile, i.e. for any estimated position at a specific location the probability that the position error is within the accuracy requirement should be at least 95%.

2.3.2 Integrity

Integrity relates to the level of trust that can be placed in the information provided by the navigation system. It includes the ability of the navigation system to provide timely and valid warnings to users when the system must not be used for the intended operation or phase of flight. Specifically, a navigation system is required to deliver a warning (**an alert**) of any malfunction (as a result of a set **alert limit** being exceeded) to users within a given period of time (**time-to-alert**). **Integrity risk**, also referred to as the probability of misleading information, is defined as the probability that the navigation positioning error exceeds the alert limit and that the event is not detected.

Loss of integrity can happen in one of two ways. Either an unsafe condition is not detected or it is detected, but the alert is not received by the user within the **time-to-alert**. The alert limit defines the largest position error, which results in a safe operation. This is specified such that the error can degrade to a level larger than the 95th percentile accuracy requirement but still within a safe limit. Time-to-alert is defined as the maximum time allowed from the moment a fault resulting in an unsafe condition is detected to the moment that the user is made aware of it.

Traditionally, some component of the navigation system and/or an independent monitoring unit assures integrity by monitoring the transmitted signals and provides a timely warning when they are out of specification. For example, LORAN-C provides system integrity by monitoring timing accuracy. Stations that exceed the system tolerance nominally 100 nanoseconds, transmit blinking signals. This starts within 60 seconds of detecting an anomaly. VHF omni-directional range aviation systems use an independent monitor to supply system integrity and remove a signal from use within 10 seconds of an out-of-tolerance condition. Integral monitors in instrument landing system and microwave landing system facilities exclude anomalous signals from use within one second (US DoD, 2000). This paper assesses how the navigation system GPS, deals with the issue of integrity and whether this satisfies the requirements in Table 1.

2.3.3 Continuity

Continuity of a navigation system is its capability to perform its function without non-scheduled interruptions during the intended period of operation (POP). It relates to the capability of the navigation system to provide a navigation output with the specified level of accuracy and integrity throughout the intended POP, assuming that it was available at the start of the operation. The POP depends on the phase of flight, for example, 1 hour for en-route. Continuity risk is the probability that the system will be interrupted and not provide guidance information for the intended POP. The risk is a measure of system unreliability.

2.3.4 Availability

Defined as the percentage of time during which the service is available (i.e. reliable information is presented to the crew, autopilot or other system managing the flight of the aircraft) for use taking into account all the outages whatever their origins. The service is available if accuracy, integrity and continuity requirements are satisfied. Unlike ground navigational aid infrastructures, the availability of GNSS is complicated by the movement of satellites relative to a coverage area and the potentially long time to restore a satellite in the event of a failure. Accurately measuring the availability of such a system would take many years, to allow the measurement period to be longer than the mean time before failure and to repair (MTBF and MTTR). Hence the availability of GNSS is determined through design, analysis and modelling, rather than measurement. True system availability can only be determined (by measurement) after the end of its life.

Table 1 GNSS Aviation Operational Performance Requirements

Operation	**Accuracy (95%)**	**Integrity**			**Continuity (1- Risk)**	**Availability**
		Integrity (1-Risk)	**Alert Limit**	**Time-to-Alert**		
Oceanic	12.4 nmi	$1\text{-}10^{-7}$/hr	12.4 nmi	2 min	$1\text{-}10^{-5}$/hr	0.99 to 0.99999
En-route	2.0 nmi	$1\text{-}10^{-7}$/hr	2.0 nmi	1 min	$1\text{-}10^{-5}$/hr	0.99 to 0.99999
Terminal	0.4 nmi	$1\text{-}10^{-7}$/hr	1.0 nmi	30 sec	$1\text{-}10^{-5}$/hr	0.99 to 0.99999
NPA	220 m	$1\text{-}10^{-7}$/hr	0.3 nmi	10 sec	$1\text{-}10^{-5}$/hr	0.99 to 0.99999
APV I	220 m (H) 20 m (V)	$1\text{-}2\text{x}10^{-7}$/approach	0.3 nmi (H) 50 m (V)	10 sec	$1\text{-}8\text{x}10^{-6}$/15 sec.	0.99 to 0.99999
APV II	16 m (H) 8 m (V)	$1\text{-}2\text{x}10^{-7}$/approach	40 m (H) 20 m (V)	6 sec	$1\text{-}8\text{x}10^{-6}$/15 sec	0.99 to 0.99999
Cat. I	16 m (H) 4.0 to 6.0 m (V)	$1\text{-}2\text{x}10^{-7}$/approach	40 m (H) 10-15 m (V)	6 sec	$1\text{-}8\text{x}10^{-6}$/15 sec	0.99 to 0.99999
Cat. II	6.9 m (H) 2.0 m (V)	$1\text{-}10^{-9}$/15 sec.	17.3 m (H) 5.3 m (V)	1 sec	$1\text{-}4\text{x}10^{-6}$/15 sec	0.99 to 0.99999
Cat. III	6.2 m (H) 2.0 m (V)	$1\text{-}10^{-9}$/15 sec.	15.5 m (H) 5.3 m (V)	1 sec	$1\text{-}2\text{x}10^{-6}$/30 sec (H) $1\text{-}2\text{x}10^{-6}$/ 15 sec (V)	0.99 to 0.99999

2.4 Summary

This Section has presented the definition of integrity and other required navigation performance parameters, and presented the corresponding aviation operational performance levels for a GNSS like GPS. The next Section presents an overview of the methods available to monitor the integrity of a GNSS.

3 Integrity Monitoring Methods

Various methods for monitoring the integrity of GNSS have been proposed in an attempt to satisfy the integrity requirements. Each method aims either to check whether an individual measurement error exceeds a specified threshold, or whether the resulting position error exceeds a specified threshold. The latter approach is more relevant to air navigation, since it is the output of the positioning system, i.e. the aircraft coordinates, which must be checked against the navigation accuracy requirements during the various phases of flight. The main approaches to the monitoring of integrity of satellite based navigation systems are:

- External monitoring.
- Receiver Autonomous Integrity Monitoring (RAIM).

It is important to note that complex systems such as GNSS also employ integral/built-in mechanisms for self-checks to offer a degree of integrity assurance. An example of this is a concept known as satellite autonomous integrity monitoring (SAIM) which is based on the monitoring of the performance of the frequency generation mechanism on board the satellite. Various checks are also built in, for example, at functional and algorithmic levels within the control and space segments.

3.1 External monitoring

External monitoring of GNSS relies on a number of ground-based stations, positioned at known locations (Fernow and Loh, 1994). Individual satellites are then monitored by comparing the measured pseudoranges with those computed from the coordinates of the satellite and monitor station. If a measurement error exceeds a certain threshold, indicating that a satellite is faulty, then a warning is sent to the users within the time-to-alert. This is a powerful approach to integrity monitoring, since it directly isolates the faulty satellite, enabling navigation to continue if sufficient satellites are still available. It is ideal for monitoring system errors (control and space segments). However, the approach is not able to identify problems local to the user (e.g. multipath and abnormal measurement noise). To address this problem, it is necessary to use a method, which relies on the actual measurements used in the positioning solution.

3.2 Receiver autonomous integrity monitoring

The receiver autonomous integrity monitoring (RAIM) method is applied within the user receiver to enable it to independently or autonomously establish system integrity. RAIM attempts to address two main concerns.

- The existence of a bad measurement.
- In the event that the above is true, the identification of the affected satellite.

It important to note that if a GNSS is used for supplemental navigation, then addressing the first concern above is sufficient because an alternative navigation system is available and can be used instead. However, if the GNSS is used for primary-means navigation, then both concerns above must be fully addressed to identify and remove the affected measurement (satellite) from the solution allowing the aircraft to safely proceed. Addressing either concern requires redundant measurements, i.e. more than the minimum four measurements required for a position solution. Hence, measurements from at least five satellites are required to detect a satellite anomaly, and a minimum of six satellites to remove the affected satellite from the navigation solution.

A RAIM technique must determine a position error and make a decision as to whether the level of error is acceptable by comparing it to the alert limit for a particular phase of flight. If this limit is exceeded, then a RAIM equipped receiver must issue a warning within the time-to-alert.

A number of algorithms for RAIM have been developed including position comparison, range comparison, residual analysis and parity checking. It can be shown that these methods are basically the same, provided that care is taken in the selection of the required thresholds. Preference for one over the other is usually for computational complexity.

RAIM has the advantages that it:

- Protects against interference with the Signal in Space (SIS).
- Exists regardless of the existence of an external monitoring capability.
- Is relatively inexpensive.
- Protects against errors due to ionospheric anomalies that may not be visible from the external monitoring network.
- Protects against residual tropospheric and local errors including multipath and measurement noise.

The reliance on redundant measurements to detect and isolate bad measurements is a major drawback because it lowers availability. It is not always possible to carry out a RAIM computation if, for instance, the user receiver is at a weak location in the coverage area of the GNSS constellation, or if satellites are masked or lost during aircraft manoeuvres.

The power of autonomous integrity monitoring could be increased by adding measurements from other instruments on board the aircraft. The technique is then no longer **receiver autonomous** but **aircraft autonomous**, AAIM. AAIM can be applied either by comparing the position solution from GNSS with that obtained by other navigation sensors, such as a barometer, or an inertial navigation system (INS), or by integrating the raw measurements from each system into a single solution (with appropriate weighting of the various measurements).

Further details of the various approaches to RAIM can be found in Brown (1996).

3.3 Summary

This Section has given a high level overview of the different methods available for monitoring the integrity of GNSS. It is important to note that because of their strengths and weaknesses, a combination that uses the two approaches (plus built in self-monitoring) may be required particularly for safety critical applications. This can be justified purely from a safety point of view given the difficulty of quantifying the performance levels achievable with such a combined approach. The next Section now looks at the current status of GPS and the methods adopted for integrity monitoring.

4 Current status of GPS integrity monitoring

This section presents the current status of the GPS architecture and integrity monitoring capability. Issues considered include the following.

- Current system status and performance specification.
- Anomalies that could result in the loss of integrity at system and user levels. This is based mainly on theoretical analysis and data from operational experience (e.g. results of studies carried out for the CAA and for the US Department of Defense).
- System level integrity provision methods.
- User level integrity monitoring capability based on receiver autonomous integrity monitoring (RAIM).

4.1 Current system status and performance specification

The global positioning system (GPS) is a US owned joint military and civilian system operated jointly by the Department of Defense (DoD) and the Department of Transport (DoT). It is an all-weather, 24-hour global 3-dimensional navigation/ positioning and timing system. The system achieved its full operational capability (FOC) on 17 July 1995 (US DoD, 2000; 2001) with a 24-satellite constellation. Because of the military use of GPS, the navigation performance available to civilian users in the past has been based on military (security) considerations. This resulted in the provision of two positioning services, **standard** and **precise** for open and restricted access respectively. The standard positioning service (SPS) provided an **artificially** degraded navigation performance (at the level of 100m, 95%) through the implementation of the effects of selective availability (SA).

Since the system achieved full operational capability, there have been continued activities aimed at improving the navigation performance (OSTP, 1996; OVP, 1998; OVP, 1999; OPS, 2000). This has arguably been driven by the shortcomings of the deployed system as observed in operation and pressure from the civilian community. The significant developments since 17 July 1995 can be summarised as follows.

- Improvements within the ground segment resulting in better navigation data determination and prediction models. For example, the accuracy and quality of the satellite orbit and clock parameters have seen considerable improvement.
- The introduction of higher specification satellites (Blocks IIA and IIR) into the constellation.
- The removal of selective availability (**dither** and **epsilon**) with effect from 04.05 UTC on 2 May 2000 (Milbert, 2000; OPS, 2000).

The impact of these developments has been to improve the system performance. For example, over the period 1993 to 2000 the mean measurement error budget seen by the user has improved from ~33 m (in the presence of selective availability) to ~7.25m (Conley and Lavrakas, 1999).

The following sub-sections summarise the current (as of November 2001) system status and performance specification.

4.1.1 Space Segment

The GPS space segment consists nominally of a constellation of 24 operational Block II satellites (Block II, IIA, and IIR). Tables 2 and 3 show the current status of the GPS constellation and the corresponding signal characteristics respectively. The **mean space vehicle (SV) life-spans** given in Table 2 are based on **operational experience** (for those satellite types which have been in operation for a considerable period of time) and **estimated live expectancy** (for those satellite types either in the early years of operation or still to be launched) (Lollock, 2001).

Table 2 The GPS Constellation as of November 2001

Orbital Configuration	SV Types	Mean SV Life-span (years)
Full Operation Capability (FOC) • **24**[1] (28) SVs • 6 orbital planes • 4 SVs per plane • 55 degree orbital inclination • orbital radius of 26,560 Km	**3**[1] (4) Block II SVs [1989][2]	**8.6** [**based on operational experience**]
	16[1](18) Block IIA SVs [1990][2]	**10.6** [**based on operational experience**]
	5[1](6) Block IIR SVs [1996][2]	**10** [**estimated**[3] **lifespan**]

1. Nominal Constellation plus SV's in additional positions as of 31.10.2001 in brackets
2. Year of first launch
3. cf. Lollock 2001

Table 3 The current GPS signal characteristics

	Definition and Characteristics	Comments
Signal Structure	Carrier Frequencies L1: 1575.42 MHz L2: 1127.60 MHz	Code Division Multiple Access (CDMA)
	Code Frequencies (Gold code) C/A-Code: 1.023 MHz (on L1)	For the Standard Positioning Service (SPS)
	Code Frequencies (pseudo random) P-Code: 10.23 MHz (on L1/L2)	For the Precise Positioning Service (PPS)
	Navigation message	Ephemeris, SV clock parameters, ionospheric parameters, SV health
Restricted signal access	Anti Spoofing (AS)	P-code degraded to Y-code

4.1.2 The control (ground) segment

The GPS Control Segment (CS) consists of four major components: a Master Control Station (MCS), Backup Master Control Station (BMCS), four ground antennas (GA), and six monitor stations (MS). The MCS is located at Schriever Air Force Base, Colorado, and is the central control node for the GPS satellite constellation. The MCS is responsible for all aspects of constellation command and control.

In the event of a prolonged MCS outage, GPS operations can be moved to a contractor-owned BMCS located at Gaithersburg, Maryland (MD). When required, personnel from the MCS deploy to the BMCS within 24 hours. The BMCS is exercised for operational effectiveness four times a year.

The satellite tracking data from the monitor stations is transmitted to the MCS where extensive modelling algorithms are applied for orbit and clock prediction. Satellite ephemeris, clock parameters and other navigation data are up-linked via the ground antennas to the satellites. This information is summarised in Table 4.

Table 4 The current GPS Ground (Control) Segment

Sub-system	Location	Functionality
Master Control Station (MCS) Backup Master Control Station (BMCS)	Schriever Airforce base (MCS), Colorado Gaithersburg, Maryland (BMCS)	• Routine satellite bus and payload status monitoring • Satellite maintenance and anomaly resolution • Managing SPS performance in support of all performance standards • Navigation data upload operations as required to sustain performance in accordance with accuracy performance standards • Prompt detection and response to service failures
Monitor Stations (MS)	Colorado Springs, Hawaii, Cape Canaveral (Florida), Ascension Islands, Diego Garcia, Kwajalein	Near real-time ranging measurement data for MCS and support of near continuous monitoring of constellation performance
Ground Antennas (GA)	Diego Garcia, Ascension, Kwajalein, Cape Canaveral (Florida)	Near real-time Telemetry, Tracking and Commanding interface between SV's and MCS

The key development within the ground (control) segment during the period 1995 to-date can be considered to have been in the refinement of algorithms and mathematical models for the determination of the navigation data for the GPS satellites.

4.1.3 GPS performance specification

The GPS Standard Positioning Service Performance (SPS) document specifies the navigation performance parameters in terms of coverage, service availability, service reliability and accuracy (US DoD, 2001). These are defined below.

- **Availability of Position Dilution of Precision (PDOP):** The percentage of time over a specified time interval that the Position Dilution of Precision (PDOP) is less than or equal to a specified value. The PDOP is a measure of the geometrical configuration of the satellites used in a position solution. The accuracy of the 3-D position solution can be estimated by scaling the PDOP value by an estimate of the measurement precision.
- **Service Reliability:** The percentage of time over a specified time interval that the instantaneous signal-in-space (SIS) SPS user range error (URE) is maintained within a specified reliability threshold at any given point within the service volume, for all healthy GPS satellites. The likelihood of the reliability threshold being broken is referred to as the Probability of Hazardously Misleading Information (HMI).
- **Service Availability:** The percentage of time over a specified time interval that the predicted position accuracy is less than a specified value for any point within the service volume.
- **Positioning Accuracy:** The statistical difference between position measurements and a surveyed benchmark for any point within the service volume over a specified time interval. The **time transfer** accuracy relative to UTC (USNO) is defined as the difference (at a specified probability) between user UTC time estimates and UTC (USNO) at any point within the service volume over a specified time interval.

Table 5 gives the navigation performance levels as specified in the GPS SPS performance standard document (US DoD, 2001). The figures quoted are for the signal-in-space (SIS) representing only control and space segment errors. In other words they do not include contributions from errors due to the atmosphere (ionosphere and troposphere), multipath, receiver or interference.

It is interesting to note that it is not possible to carry out a complete one-to-one mapping between the ICAO RNP parameters and those used to specify GPS performance. In particular, there is no specification placed on integrity. In fact, the GPS SPS performance standard document states that GPS SPS performance is not currently monitored in real time.

Table 5 Current SPS performance levels

Navigation parameter	Specification
PDOP Availability Standard	≥ 98% global Position Dilution of Precision (PDOP) of 6 or less ≥ 88% worst site PDOP of 6 or less
Service Availability Standard (based on WSPDA)	≥ 99% Horizontal Service Availability average location ≥ 99% Vertical Service Availability average location ≥ 90% Horizontal Service Availability worst-case location ≥ 90% Vertical Service Availability worst-case location
Service Reliability Standard	≥ 99.94% global average ≥ 99.79% worst case single point average
SPS SIS URE Standard	≥ 6 meters RMS SIS SPS URE across the entire constellation
Accuracy Standard	
Global Average Positioning Domain	≤ 13 meters 95% All-in-View Horizontal Error (SIS Only) ≤ 22 meters 95% All-in-View Vertical Error (SIS Only)
Worst Site Positioning DomainAccuracy (WSPDA)	≤ 36 meters 95% All-in-View Horizontal Error (SIS Only) ≤ 77 meters 95% All-in-View Vertical Error (SIS Only)
Time Transfer Accuracy	≤ 40 nanoseconds time transfer error 95% of time (SIS Only)

4.1.4 The user segment

The breakdown and estimates of the contribution of the different error components to the range error experienced by the user, i.e. the user equivalent range errors (UERE) including both system and user environment errors, are given in Table 6. Note that for those errors that are elevation dependent, the figures quoted are for the zenith in which case the relevant mapping functions are required to convert them to slant range errors. The total UERE error budget can be scaled by the relevant dilution of precision parameters to estimate the position accuracy. For example, with a horizontal dilution of precision (HDOP) of 2.0, the corresponding estimates of horizontal positioning accuracy would be 8.8, 29.2 and 58.4 m (2σ), for the best, average and worst ionospheric error cases respectively.

Real field data collected after the removal of the effects of selective availability has shown that position accuracy better than 20 m (2σ) is routinely achievable (Conley and Lavrakas, 1999).

Table 6 Typical User Equivalent Range Errors

Error Source	SPS (m, 1σ)		
NAV message curve fit	0.2		
Orbit	0.57		
Satellite Clock	1.43		
C/A Code Phase Bias	0.27		
Receiver Noise	0.8		
Tropospheric Error	0.25		
Ionospheric Error (Single Frequency; standard correction model)	1.3 (best site)	7 (average)	14.40 (worst site)
Total UERE error budget (Single Freq.)	2.2	7.3	14.6

4.2 Failure modes

GPS is a complex system, based on data messages transmitted from a constellation of satellites. There is a potential for failure at any one of a number of stages, from the production of the data messages and their upload to the GPS satellites, to their transmission, reception and processing within the user receiving equipment. The following sub-sections present a number of things that could go wrong (and result in loss of integrity) at system, operational environment and user receiver levels. The lists have been compiled from a number of sources (Barker and Huser, 1998; Cobb **et al.**, 1995; Walsh and Daly, 2000; Pullen **et al.**, 2001) and contribute to the justification for the need for integrity monitoring.

4.2.1 System level

System level failures, such as these in Table 7, are those that occur within the space segment, the control segment, and the interface between the two (i.e. data transmission). Such failures, for example, due to weaknesses in satellite design and algorithms within the MCS environment, mainly result in excessive range errors. The failure modes are listed in six categories; those related to erroneous clock behaviour, incorrect modelling and malfunction of the MCS, satellite payload performance, space vehicle performance and RF performance. In each case a high level analysis of impact has been carried out and in some cases the impact has been quantified.

Table 7 GPS system level failures

Performance failures related to erroneous clock behaviour	**Comments**
• Satellite specific clock misbehaviour (based on type of atomic time standards used) often not detected. No notification is given either within the navigation message or through NANU. • Satellite clock jumps leading to excessive pseudorange deviation • Malfunctions in the atomic frequency standards • **Actual failure:** . *In July 2001 a GPS satellite had a clock failure which caused range errors of thousands of meters. The error lasted for approx 90 minutes (Clock failures are one of the most common GPS failures).*	• This can result in excessive code and carrier noise up to range errors of several thousand metres • Drifting L1/L2 frequencies leading to wrong range and Doppler measurements and loss of lock
Performance failures related to incorrect modelling and malfunction in the MCS	
• Incorrect modelling of orbital parameters during and after a period of eclipse because of excessive temperature gradients leading to the need of more frequent navigation uploads. The kalman clock state does not show a clear convergence • Incorrect modelling in the MCS Kalman filter due to shortcoming in the weighting mechanism • **Actual failure:** *A failure occurred on 12-22 March 1993 due to erroneous modelling of the satellite orbits resulting in the broadcast of incorrect satellite co-ordinates. The failure caused ranging errors to increase steadily over the course of nearly two weeks. This did not show up in the performance monitoring system at the time. The range errors were up to 40m.* • **Actual failure:** *A failure occurred which was caused by incorrect modelling of the orbital parameters during and after a period of eclipse. The effect was seen as a steadily increasing range error.*	This can result in wrong satellite altitudes leading to wrong range measurements due to wrong ephemeris data
Satellite payload related performance failures	
• Non-standard code due to open time keeping system (TKS) loops (Block IIR). If this happens as the same time the telemetry is output by the navigation data unit (NDU), a reset of the main processor may occur • Erroneous or corrupt navigation data due to several reasons (e.g. the ionisation of silicon material used in memory devices by heavy ion cosmic rays and energy particles from the sun) leading to degraded navigation performance • **Actual failure:** *A failure which caused a range rate error, a range jump and a loss-of-lock was detected by the CAA ISN as part of the GPS monitoring project performed for the SRG. The likeliest cause for this error was an upload from a control station causing a temporary internal hardware failure.* • **Actual failure:** *A 6 second loss-of-lock event regarding PRN 17 was reported in 1995. Similar outages were observed on most of the Block II satellites. The satellite operators stated that this was a generic spacecraft problem caused by command uplinks to Block II satellites, which caused a conflict in the spacecraft computer.*	• This can lead to incorrect navigation data or range errors • Satellites reset their processors every 24 seconds (Block II/IIA) to monitor quality of navigation data (e.g. stored in memory). Block IIR satellites use a watch dog monitor (WDM) to decide when a reset must occur.

Table 7 GPS system level failures

Failures related to satellite orbits	
• Trajectory changes when a satellite has come out of the eclipse • The Doppler or Doppler rate may be out of specification due to SV manoeuvres • Instabilities in the satellite attitude • Miscalculated satellite orbits	Range errors up to 30m could occur
Space vehicle system related performance failures	
• Degraded attitude control systems leading to range errors due to malfunctioning hardware devices and excessive solar interference in the vicinity of the eclipse • Dramatic transmission power fluctuation (i.e. +/-20 dB per 1 sec) • Erroneous PRN code i.e. code does not correspond to any SV in the constellation or to a different one • **Actual failure:** *a reaction wheel failure for a satellite was reported which caused instability in the satellite attitude causing range errors of about 24m initially and then maximum range errors of almost 90m before stabilisation.* • **Actual failure:** *Ionospheric scintillations during a solar storm caused a space vehicle to go into nuclear detection mode in which it moved off its normal orbit*	• Leads to malfunction in the channel tracking • Increased signal-to-noise (SNR) causing incorrect range measurements • Receiver fails to acquire SV signal or loss-of-lock • Wrong signal polarisation and data parities
RF related performance failures	
• Onboard RF filter failure leading to corrupted side lobes • Unstable L1, L2 or L1-L2 RF delays in the SV (i.e. sudden jumps or slow fluctuation over time) • Onboard multipath and onboard signal reflection • De-synchronisation between data modulation and code • Onboard interferences and inter-channel bias	• Leads to corruption of the transmitted spectrum • Could result in range errors up to several meters

4.2.2 Operational Environment

These failures are mainly due to interference (intended and unintended) and the effects of the media along the signal path. In Table 8 the failure modes are listed in three categories; intended interference, unintended interference and signal propagation. In each case a high level analysis of the impact has been carried out.

The primary signal characteristic that makes GPS vulnerable to interference is the low power of the signal. A receiver can loose lock on a satellite due to an interfering signal that is only a few orders of magnitude stronger than the minimal received GPS signal strength (10-16 watt, equivalent to – 160dBw). A receiver trying to lock on to a GPS signal requires 6 to 10 dB more carrier-to-noise ratio than required for tracking (Niesner and Johannsen, 2000; Volpe, 2001). The intervening media between the satellite and the antenna also affect signal propagation. This includes the effects of the ionosphere, troposphere and multipath.

Table 8 Operational environment level failures

Intended Interference	**Comments**
• **Jamming:** Intentional interference or jamming i.e. emission of sufficiently powerful enough radio frequency energy. This is either realised as emission of signal close to the GPS spectrum or if more sophisticated as emission of a GPS like signal. Civil receivers are vulnerable. • **Spoofing:** Is the intended injection of false GPS like signal. The receiver will lock onto a legitimate appearing signal.	• This could prevent GPS receivers from tracking the signal or cause frequent loss-of-lock. (positioning error up to 600 m) • Sophisticated jamming technology could prevent a receiver from acquiring the signal. • Spoofing, if not detected, could inject hazardous misleading information (HMI) and cause significant navigation errors.
Unintended RF Interference	
• Interference from RF transmitters emitting unwanted signal power in the L1/L2 band (e.g. Ultra wideband Radar and communications Broadcast television, VHF, Personal Electronic devices, Mobile satellite services etc.) • The new proposed L5 signal partially overlaps with for example the military Joint Tactical Information Distribution Service (JTIDS) and other commercially used similar services.	• This might lead to receivers having difficulty tracking the GPS signal or losing lock.
Performance failures related to sudden changes in the signal propagation properties	
• The ionosphere surrounding the Earth refracts radio signals in the L1, L2 and the proposed L5 band. Therefore small-scale (spatial and temporal) electron density fluctuations especially in periods of high solar activity may affect the GPS signals significantly causing non-integrity or non-availability situations. • The troposphere has the effect of bending and refracting (delaying) the navigation signal. The bending effect is very small and can be neglected. • Multipath errors result from reflection of the navigation signal off surfaces, which disturb the code and carrier-tracking loop.	• For single frequency receivers the ionospheric effect might result in range errors up to 100 m. • Certain Ionospheric effects may lead to rapid changes in the phase of the signal causing loss-of-lock. • The delay due to the troposphere can vary from 2 to 25m. Most of this effect can be modelled. However sudden changes can cause potential non-integrity scenarios. • Multipath error is location specific and can be difficult to model. Could result in range errors of hundreds of metres.

4.2.3 User receiver

These failures relate to the end user and the end-user equipment i.e. receiver and receiver software. Failures related to humans include the lack of adequate training, over-reliance on a single navigation system etc. It is important to state that receivers for use with GPS for safety critical applications such as aviation must be certified to meet the minimum standards as specified by the relevant authorities. This certification process must also be as vigorous as possible to ensure that no failures such as those observed on some certified receivers do not occur (Niesner and Johannsen, 2000). Table 9 gives a high level overview of potential receiver level failure modes. Human related failures have been added to give a more complete picture.

Table 9 User receiver level failures

Receiver/ user related performance failures

- There have been cases of some receivers, particularly low-cost in-car and handheld units not having been designed to meet the basic receiver hardware and software requirements. In one case the developer had assumed the values for IODE/IODC would never reach $F0_{16}$. Operational testing later showed this not to be the case. Furthermore, there have been cases where unhealthy satellites have also been included in the navigation solution.
- There is statistical evidence that even GPS receivers certified for civil aviation (RTCA/ DO-208) fail to provide the required navigation information (Niesner and Johannsen, 2000). Receivers shutdown, pause suddenly, or even provide seriously incorrect positions. These failures can be attributed to:
    - power system failure or power fluctuations
    - software incompatibilities (year/week rollovers)
    - receiver unit overheating
    - instabilities in the quartz frequency standards
    - receiver interface outages
    - receiver outages related to excessive electromagnetic activities (lightening etc.)
    - hardware incompatibilities if the GPS unit is coupled with other means of navigation (i.e. INS, compasses, external clocks, air data, navigation data bases etc.)
    - processing algorithm errors
- GPS receivers comprise complex hardware and software which are vulnerable to failure
- Hard-wired and incorrect RAIM parameters have been used in certified receivers
- **Actual failure:** *Many certified receivers failed to cope with the Y2K event and the GPS rollover*
- **Actual failure:** *As part of the CAA ISNs monitoring programme certified receivers have been seen to output position errors of thousands of metres. The main cause is simply badly formatted output through the certified output port.*
- **Actual failure:** *An error in the GPS derived position of 8nmi was reported on 16/2/99 in the North Sea area.*

Human related failures

- According to the GPS vulnerability study, most of the accidents to date involving the use of GPS have been the result of human factor issues (Volpe, 2001). The following examples show the significance of this statement.
    - cases where pilots were trained inadequately in the use of GPS for navigation
    - pilots were found to be more likely to take greater risks during the flight regarding the weather if the plane is equipped with GPS instead of only with traditional navigation aids
    - cases where pilots travel into restricted airspace while using GPS because they felt greater flexibility to leave the traditional route structure.

4.3 System level integrity monitoring

Protection against anomalies and failures such as those listed in Sections 4.2.1, 4.2.2 and 4.2.3 (receiver related errors) is assured at two levels. The first is by relying on satellite self-checks and monitoring by the US DoD Operational Control Segment (OCS) Master Control Station (MCS), and the second through signal assessment by users. Thus GPS has both integral and independent mechanisms for integrity monitoring. User level integrity is addressed in 4.4.

The control segment maintains the system clock, calculates the satellite orbit and clock error, and monitors and controls the system behaviour. Operations are carried out on the measured pseudoranges in order to detect outliers (anomalies), and to reduce measurement noise. The received signal strength is also checked and the navigation data carefully checked before upload. The data is transmitted with an error protection code (i.e. parity and sum check). Some self-check functions are also used in the space segment including parity checks, navigation data, frequency synthesiser, anti-spoofing generation and memory checks.

4.3.1 Satellite self-checks

GPS satellites internally monitor themselves for some, but not all, anomalies. These include navigation data errors, anti-spoof and certain types of satellite clock failures. If such internal failures are detected, satellites notify users within six seconds. Navigation data failures, for example, can occur because of data corruption. Satellite navigation electronics are susceptible to damage from the space environment. Heavy ion cosmic rays and energetic particles from the sun can ionise silicon material when they pass through it, causing a bit flip or bit hit (also known as single event upset) in memory devices and thereby corrupting the stored data. To prevent bit hits from affecting navigation data in Block II and IIA satellites, these data are stored in specially hardened, electrically-alterable, read-only memory (EAROM) that is almost impervious to bit hits.

A satellite's navigation processor refreshes scratch-pad, random-access memory every six seconds with data pulled from the EAROM. In the unlikely event that EAROM data are corrupted and the appropriate navigation data cannot be found, the satellite will output (for the next six seconds) default navigation data, which consists of alternative ones and zeros in words three through ten, with invalid parity of the affected words. Each word in the satellite navigation message contains parity bits that are used to verify the correct transmission of the navigation message from the satellite to the receiver. Therefore, the longest that a loss of navigation data could persist because of a bit hit would be six seconds. For further protection, a satellite resets its processor every 24 seconds so that, if the address pointer is accidentally moved to an erroneous position in memory, it will recover to a known location within 24 seconds.

The Block IIR satellites use a different equipment architecture to protect against bit hits. They have a watch dog monitor (WDM) that regulates the functioning of the processor, and decides when a processor reset must occur. If the WDM performs a processor reset, the satellite transmits non-standard codes until it either automatically reverts to standard codes or the MCS commands it to do so after resolving the cause of the reset. Users are also informed of some anomalies by way of the navigation message hand-over word HOW). The HOW contains an alert flag in bit 18 that informs civilians ("unauthorised") users that the satellite's user range error may be worse than indicated in the message sub-frame 1.

4.3.2 Master Control Station Checks

The GPS constellation is monitored by the MCS at Schriever Air Force Base (formerly known as Falcon Air Force Base). Using data collected by the monitor stations distributed around the globe, the MCS assesses GPS performance every 15 minutes by conducting tolerance and validation checks of the measured pseudoranges using a Kalman filter error management process. In some circumstances, ranging errors could go undetected by this process for as long as 29 minutes. To mitigate any potential problems from such long delays, the MCS installed new software in February 1995 to check incoming range measurements every six seconds. When the software detects an anomaly, it raises an alarm. Reaction to the alarm typically occurs within 1 minute. After confirming an anomaly, MCS staff renders the offending satellite's L-band signals not trackable. The MCS accomplishes this using a technique known as SATZAP, which sends a single command telling the satellite to change its pseudorandom noise (PRN) number to PRN 37, a non-operational number. The SATZAP procedure takes five minutes or fewer to accomplish and helps resolve detected integrity anomalies within 10 minutes of initial detection, assuming a good monitor station and ground antenna visibility. Because this procedure also affects control segment tracking, MCS uploads new navigation message information to the satellite with a "bad" space vehicle health tag, before reassigning the satellite its original PRN number.

Details of the non-standard ranging codes and the meaning of message alert flags and satellite health codes are described in the Interface Control Document (ICD)–GPS-2000. In addition to altering satellite navigation messages to inform users of health problems, the MCS issues the so-called Notice Advisory to Navstar Users (NANUs) that report satellite outages as well as planned service losses caused by maintenance.

4.3.3 Summary

Although the GPS control segment and the satellites themselves provide a reasonable level of integrity, anomalies could go undetected for too long a period for some applications (see Table 1 for time-to-alert requirements for civil aviation). It typically takes the MCS 5 to 15 minutes to remove a satellite with a detected anomaly from service. Furthermore, if a satellite is not in the view of one of the ground stations (the ground stations provide only 92 percent tracking coverage), an anomaly could go undetected for a longer period of time before the MCS can realise the situation and take remedial action. Hence, this approach is not adequate for aviation.

4.4 User level integrity

As stated in Section 3.2, RAIM is a method employed within the user receiver to detect and preferably isolate any measurements, which cause significant errors in the computed position. The technique is sensitive not only to errors occurring in the GNSS system, but also to those caused by the user receiver and operational environment. The basic input to a RAIM algorithm is the same raw measurements used to compute the user's position.

RAIM availability is a concept that is applied to assess whether the right conditions exist to be able to perform a RAIM calculation, i.e. whether RAIM is 'available' to the user, as an integrity monitoring technique. The capability of a receiver to perform a RAIM calculation depends on the number of satellites, their geometry and predicted measurement quality. Thus, using only the user receiver coordinates, the predicted positions of the satellites and an estimate of the measurement quality, it is possible to determine whether or not a RAIM calculation can be performed. Since actual measurements are not required, this is a vital tool that can be used to predict whether or not it would be possible to carry out a RAIM calculation at some future point in time.

A high level assessment of the RAIM availability of the current GPS constellation has been carried out over the entire globe at spatial and temporal sampling intervals of 5 degrees and 5 minutes respectively. The assessments have been carried out for the non-precision approach (NPA) and precision approach (APVI and APVII) phases of flight, taking into account the integrity requirements given in Table 1. A statistic has been produced for each grid node (spatial sampling point) in terms of percentage availability over a period of 24 hours. Figure 1 shows the RAIM availability for NPA using a horizontal alarm limit (HAL) of 556 m. It can be seen that the availability of RAIM as an integrity monitoring technique for horizontal positioning for NPA is less than 98% in the mid latitude regions, with other regions experiencing near 100% availability.

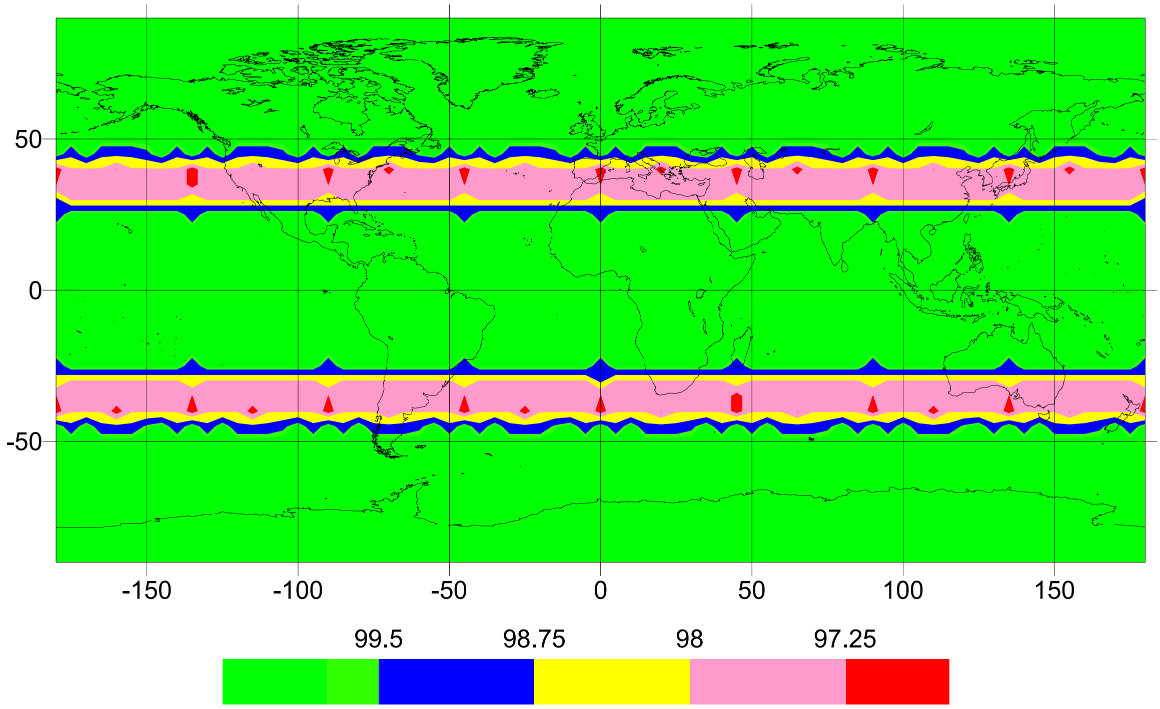

Figure 1 NPA Current Horizontal RAIM Availability

Figures 2 and 3 show the corresponding horizontal RAIM availability for precision approaches, APVI and APVII. The APVI results are similar to NPA since the requirements are largely the same. The APVII results are comparatively worse as a result of more stringent requirements (e.g. HAL of 40 m compared to 555 m for APVI). Equatorial regions experience better than 97% availability, with the rest below.

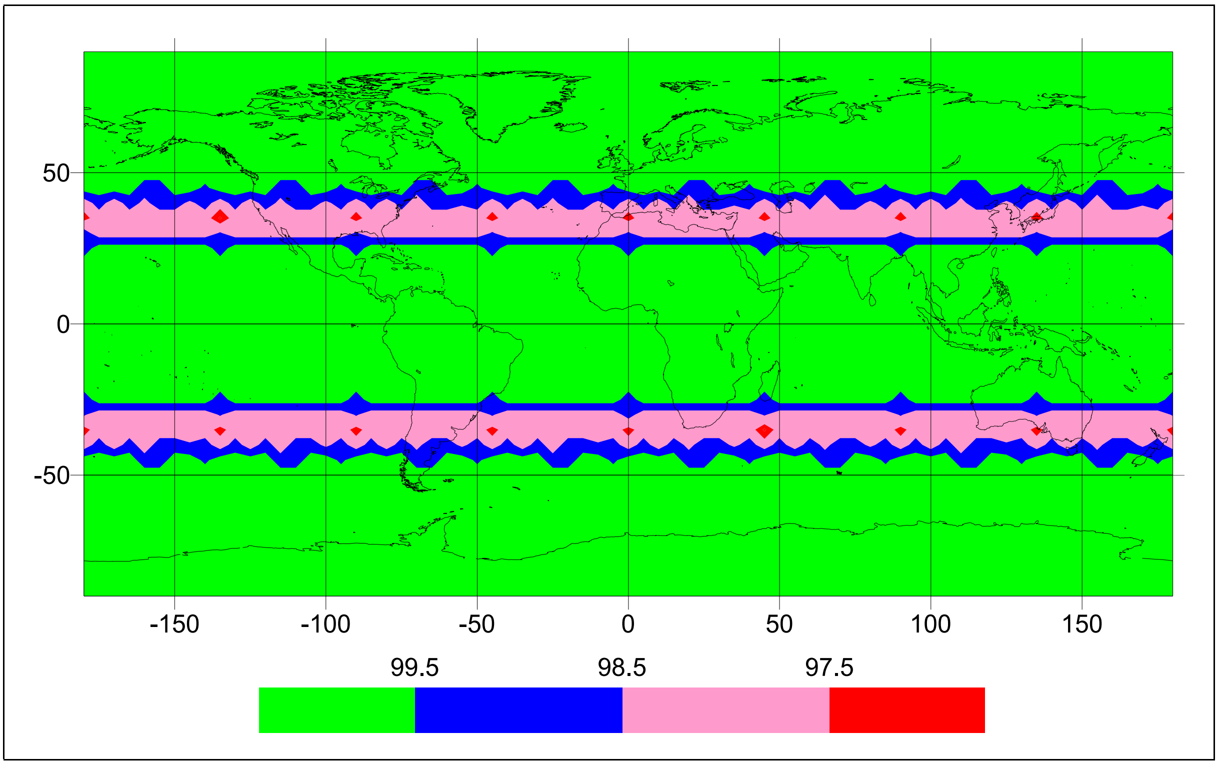

Figure 2 APVI Current Horizontal RAIM Availability

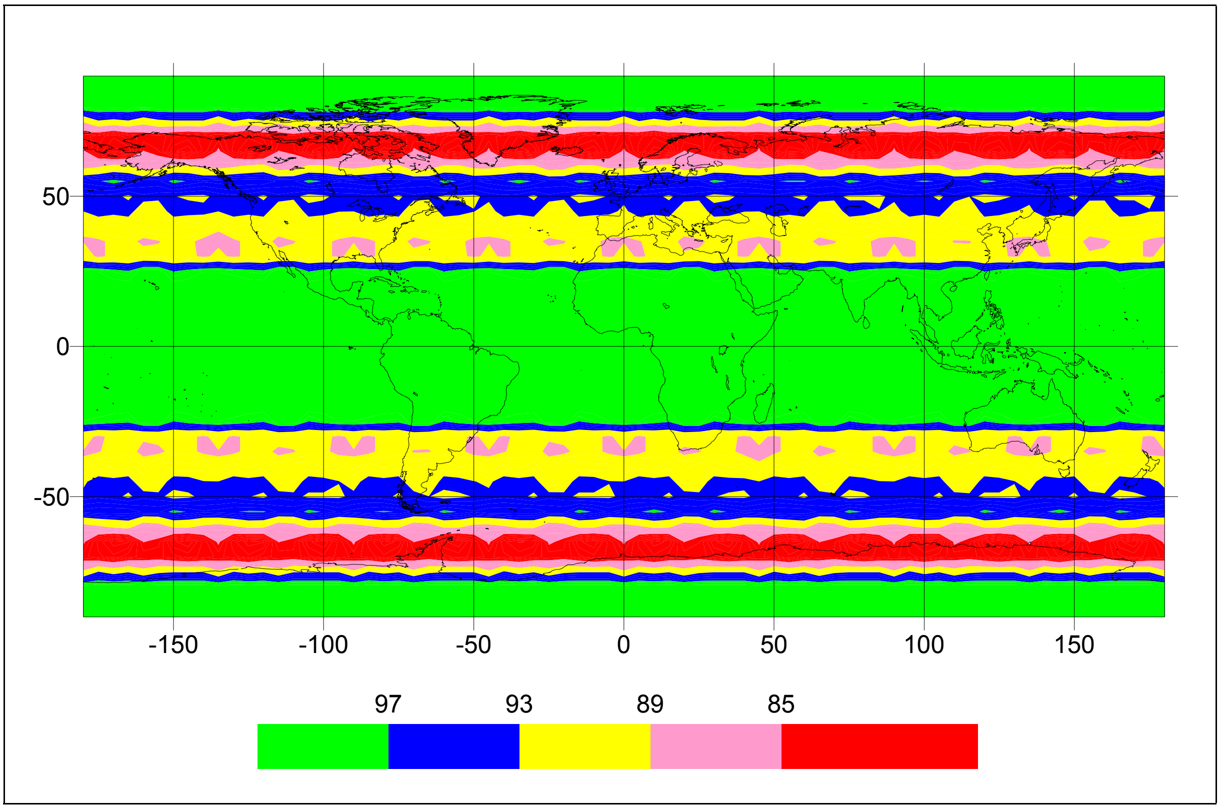

Figure 3 APVII Current Horizontal RAIM Availability

RAIM availability plots for the vertical components are shown in Figures 4 and 5 for APVI and APVII respectively. Because the vertical accuracy and the corresponding alarm limit requirements for precision approach are more stringent than horizontal, RAIM availability is considerably worse. For APVI (e.g. VAL of 50 m), the near equatorial regions experience better than 95% availability of RAIM for integrity monitoring. The mid latitude areas experience between 95 and 65% availability, with the rest generally below 65%. For APVII, with even more stringent requirements than APVI (e.g. VAL of 20 m) most of the earth experiences availability of less than 35%, with only the mid latitude areas fairing better with availability figures between 35 and 45%.

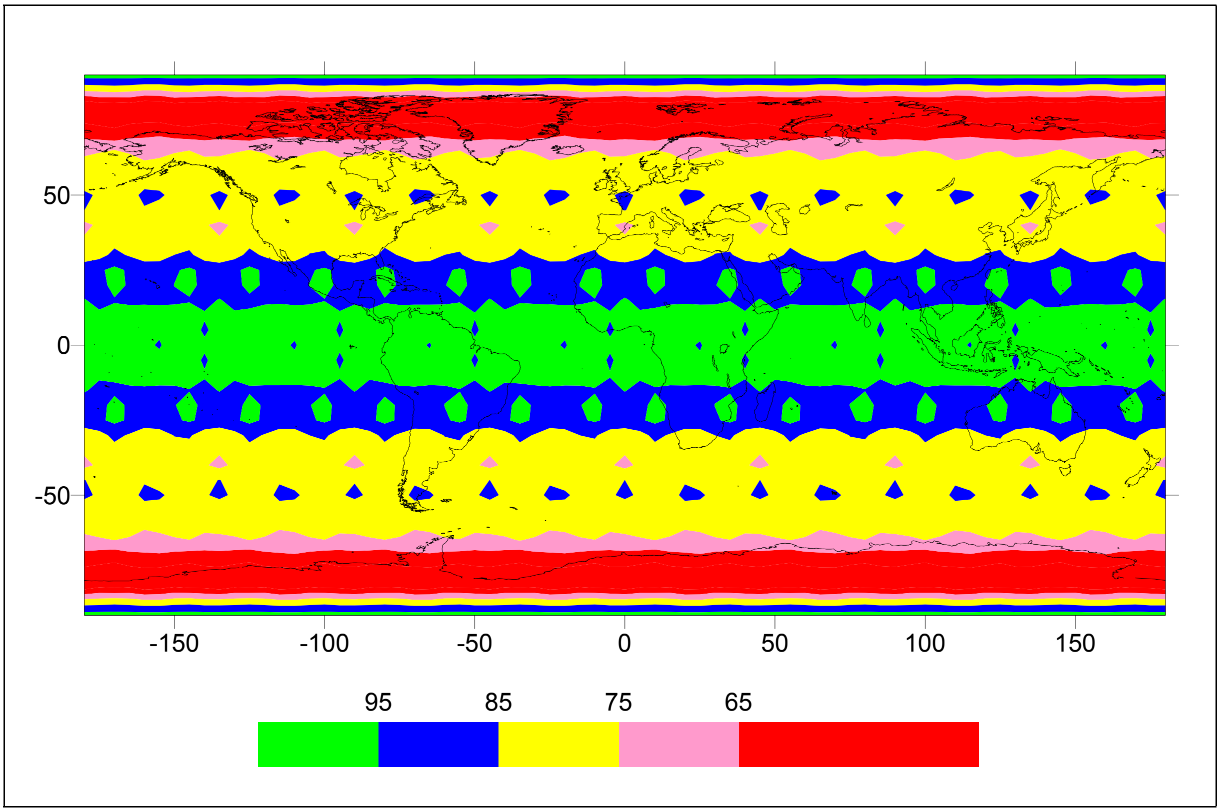

Figure 4 APVI Current Vertical RAIM Availability

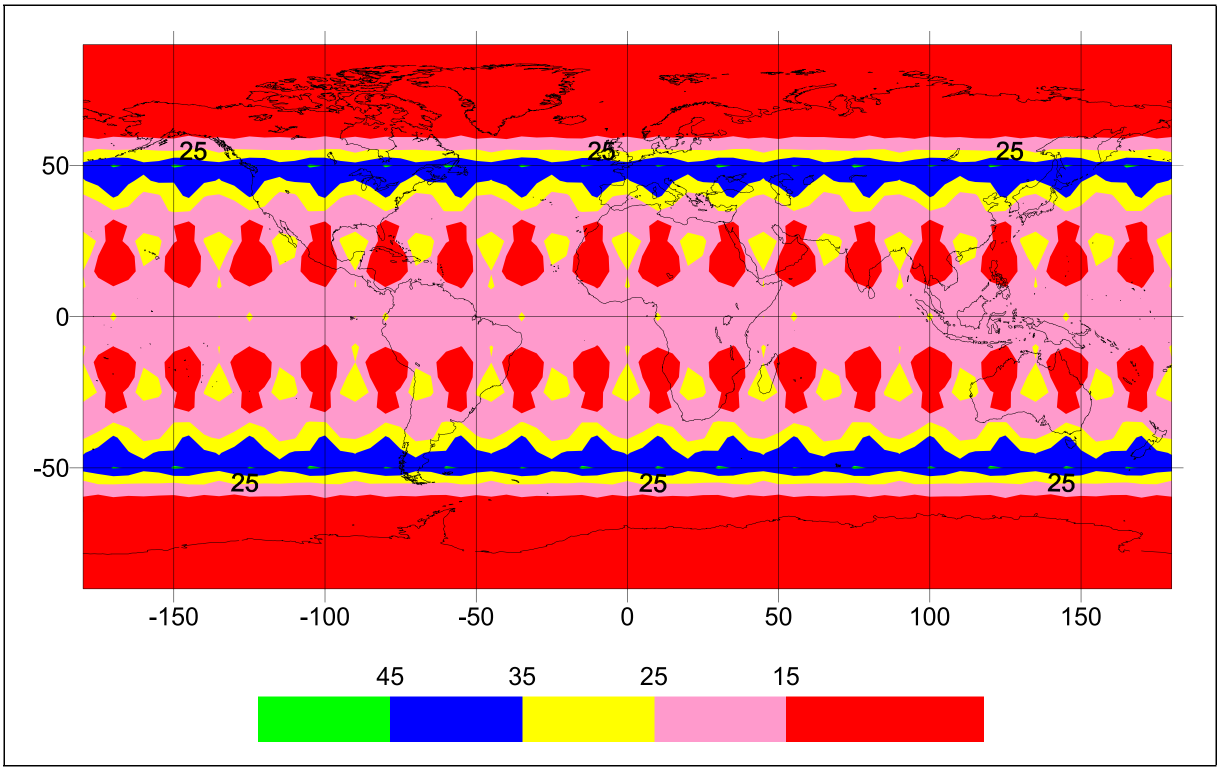

Figure 5 APVII Current Vertical RAIM Availability

Based on the RAIM availability results given above, it is clear that user level integrity monitoring using RAIM is not sufficient to meet the requirements for NPA and PA phases of flight. Given that the requirements for CAT I, II and III are even more stringent than PA, the RAIM availability for these phases will be much lower.

4.5 Summary

This Section has presented the current status of the GPS architecture and integrity monitoring capability. Potential failure modes of the system have been listed to justify the need for integrity monitoring and assurance. Three categories of failures have been identified (Tables 7, 8 and 9).

- **System level failures:** These are failures that could occur within the GPS operational control system in the ground segment and within the space segment. Example sources of failure include erroneous clock data, incorrect modelling and malfunction in Master Control Station (MCS), and satellite related instabilities (satellite payload, satellite orbits, space vehicle control, radio frequency).
- **Operational level failures:** These are failures that could occur as a result of factors associated with the operational environment. Example sources of failure include intended signal interference, unintended signal interference and sudden changes in the signal propagation properties within the atmosphere.
- **User and User Equipment level failures:** These are failures that could be induced by the receiving equipment and the user. Example sources of receiver-induced failures include those related to hardware and software.

This has been followed by a detailed analysis of the current mechanisms adopted for monitoring the integrity of GPS both at system and user levels. RAIM availability analysis results have been presented to quantify the capability of integrity monitoring at the user level.

The results of the investigation have shown that the current system level integrity monitoring mechanisms are grossly inadequate for the navigation requirements for real time safety critical applications, such as aviation. It has also been shown that user level integrity monitoring through receiver autonomous integrity monitoring is also not adequate.

The next Section looks at the future of GPS with a particular emphasis on integrity monitoring.

5 GPS Modernisation and integrity monitoring

GPS achieved full operational capability (FOC) on 17 July 1995 with 24 operational satellites (US DoD, 2000). For many applications GPS delivers a widely accepted service with performance levels that often meet the requirements for the particular application. However, as has been shown in previous sections, for other requirements including high integrity safety-of-life critical applications such as aviation, the current system does not provide the required navigation performance (RNP). Because of the huge potential market for satellite navigation services, the end of the cold war, developments in satellite navigation systems in other parts of the world, and technological developments in security related areas, the US government has put in place initiatives aimed at enhancing the performance of the system whilst still maintaining its crucial military role. Since 1996 several official announcements have been made in support of this.

- **Accuracy Improvement Initiative (AII)**: The AII effort is aimed at improving the navigation accuracy for the restricted precision positioning service (PPS). Under the AII an exhaustive analysis of the performance of the operational (ground) control system (OCS) has been carried out. This has already led to the upgrade of the OCS to support the Block IIR autonav functionality (Malys, **et al.**, 1997). With the removal of the effects of selective availability (SA), the AII already benefits both PPS and SPS users.
- **Presidential Decision Directive (PDD)**: In March 1996, a PDD was given on a US GPS Policy aimed at the management of GPS to support and enhance US economic competitiveness and productivity while protecting US national security and foreign policy interests (OSTP, 1996).
- **Navigation Warfare (NAVWAR)**: NAVWAR was initiated by the US Department of Defense (DoD) to protect the use of GPS by DoD and allied forces in times of conflict within the theatre of operations, to prevent the use of GPS by adversary forces and to preserve routine GPS service to all outside the theatre of operations.
- **US government announcement on 2nd civilian signal**: In March 1998, the US Vice-President's Office announced the intention to provide a second civilian signal (OVP, 1999).
- **GPS modernisation**: In January 1999, the US Vice-President's Office announced a $400 million (five-year) initiative to improve GPS services to civilian users. The key element of this is the decision to provide a third civilian frequency for safety-of-life critical applications (OVP, 1999).
- **GPS accuracy degradation**: In May 2000, the US president announced the discontinuation of artificial degradation of GPS accuracy through the process of selective availability (SA). This measure was a significant step in an on-going effort to make GPS more responsive to civil and commercial users worldwide (OPS, 2000).

- **GPS III initiative**: The GPS III initiative is long term and has the objective of providing military and civilian users improved capabilities from GPS to fully support safety critical applications such as aviation**.** The first GPS III satellite is to be launched in 2009, with an eventual 30-satellite constellation to serve users until around 2030 (Lee **et al.**, 2001). The FOC is estimated to be achieved around 2020. The GPS III program is currently in the requirements definition and preliminary design phases.

The following sections summarise the planned modernisation activities in detail using information from official sources. These are presented in two categories, short to medium term and long term. The initiatives given above with the exception of GPS III are considered under short to medium term. GPS III is a long-term initiative and is therefore dealt with separately. The activities are described for the space, ground and user segments. Each of the two categories is concluded with a high level assessment of the impact of the modernisation activities on integrity at both system and user levels.

5.1 Short to medium term modernisation initiatives

5.1.1 Space Segment

Tables 10 and 11 show the planned modernisation activities for the GPS constellation and the signal characteristics respectively. According to the Federal Radio-navigation Plan, **"the DOD will maintain a 24-satellite constellation. Replacement satellites will be launched on an expected failure strategy"** (US DoD, 2000). To realise the proposed changes, new generations of satellites are currently under development. These are the **modified Block IIR** satellites with the capability for a second C/A code on L2 frequency and **Block IIF** satellites with the capability for the third civilian frequency L5 (for safety critical applications). A progressive launch strategy will result in an initial operation capability in 2012 and the full operational capability (FOC) in 2014 (Lollock, 2001). For military applications the M_E code will be fully available in 2008.

Table 10 Planned satellite launch activities

SV Types	Launch Time-Frame	Capabilities	Mean SV Life-span (years)
6 unmodified Block IIR satellites	2000-2003	Current Capabilities (cf. Chapter 2)	**7.84** [*based on predicted life-span at the design stage*]
12 modified Block IIR satellites	2003-2006	C/A code on the L2 carrier frequency -new military M_E code on L1 and L2 carrier frequencies	**7.84** [*based on predicted life-span at the design stage*]
13 Block IIF satellites	2005-2010	As IIR modified + 3rd civil frequency (L5)	**12.7** [*based on predicted life-span at the design stage*]
11 Block IIF satellites	2007-2014	As IIR modified + 3rd civil frequency (L5)	**12.7** [*based on predicted life-span at the design stage*]

Table 11 Planned modernisation of GPS signals

Current Frequency Plan	**Planned Frequency Plan (additional)**	**Capabilities**
Carrier Frequencies L1: 1575.42 MHz L2: 1227.60 MHz	Additional civilian Frequency L5: 1176.45 MHz ("Safety of life" service frequency protection (ARNS-Band)) IOC-2012 FOC-2014	• 6 dB higher power relative to L1 • 20 MHz broadcast bandwidth • Improved signal Cross-Correlation properties
Code Frequencies (pseudo random) P-Code: 10.23 MHz (on L1/L2)	M_E Code (L1/L2) IOC-2008 FOC-2010	M-code designed to *enhance system security* and to improve *anti jamming*
Code Frequencies (gold code) C/A-Code: 1.023 MHz (on L1)	C/A Code on L2 (1127.60 MHz)	• dual frequency ionospheric correction (improved UERE and better accuracy)
Navigation message	Ephemeris, SV clock parameters, ionospheric parameters, SV health	On L1 , L2 and L5

5.1.2 Control Segment

To support the changes in the space segment and to exploit the enhancement to a full extent, changes in the ground (control) segment are necessary. These are mainly aimed at better tracking and derivation of navigation data. The planned activities include the following (Malys **et al.**, 1997).

- Upgrade of Monitor Station and Ground Antennas with new digital receivers.
- Replacement of existing MCS mainframe computer with a distributed architecture.
- Addition of the so-called Air Force Satellite Control Network.
- Enlargement of the tracking network by incorporating the National Imagery and Mapping Agency (NIMA) tracking stations.
- Addition of full Block IIR and IIF command and control functionality.
- Refinement and improvement of the navigation data algorithms and models, including an update of the OCS Kalman filter estimation process.
- A new upload strategy to reduce the orbit prediction error.
- Control M-code and L5.
- Incremental software versions and hardware upgrades to support modernisation.

The above activities should improve the contribution to the navigation system error by the control segment (i.e. orbit and clock errors) to 0.4 m for zero age orbital and clock estimates. The corresponding figure for navigation data prediction after 24 hours is 1.3 m.

5.1.3 User Segment

Table 12 gives an estimate of the typical user range errors (m, 1σ) (Turner **et al.**, 2000) and the corresponding horizontal positioning accuracy (at 2σ and assuming a value for HDOP of 1.5) as a result of the planned modernisation activities. From this, it is clear that the modernisation of the OCS and space segment will bring continued improvement on the expected performance (at least in terms of accuracy).

Table 12 User impact of different stages of GPS modernisation

Error Source	**Without SA (m)**	**Without SA + two C/A (L1/L2) (m)**	**Without SA + two C/A (L1/L2) + OCS Modernisation (m)**
Clock and Ephemeris Error (SS/CS)	2.3	2.3	1.25
Ionospheric Error	7	0.01	0.01
Tropospheric Error	0.2	0.2	0.2
Receiver measurement Error	0.6	0.6	0.6
Multipath	1.5	1.5	1.5
Total UERE error budget	7.5	2.8	2.0
Stand-alone Horizontal Accuracy, 95% (HDOP 1.5)	22.5	8.5	6.0

Other significant benefits will include the following:

- Better system level integrity through improvement in robustness of the system.
- Enhanced accuracy through the use of dual frequency data to correct for the effects of the ionosphere enabling more requirements to be satisfied.
- Reduced transmission rates for DGPS corrections, because SA is set to zero.
- Better real-time integer ambiguity resolution (e.g. tri-laning, three carrier phase ambiguity resolution). Therefore, real-time sub-centimetre accuracy for engineering and scientific applications should be feasible with a higher reliability.

5.1.4 System level integrity

In the short to medium term, the system level integrity will benefit from better internal (built-in) self checks mainly through more robust algorithms and the use of more tracking data from an enhanced tracking network of ground stations. No external (independent) monitoring is proposed.

5.1.5 User level integrity

The user level integrity for modernised GPS has been measured by carrying out RAIM availability analyses similar to the ones carried out for the current system. In order to do this it was necessary to predict the future status based on planned launch schedules. The constellation used in the study is for 2014 when a full constellation of BLOCK IIF satellites will be operational in a nominal 24-satellite constellation. This constellation together with the corresponding UERE budget (last column of Table 12), have been used for the availability analysis.

Figures 6 and 7 show the horizontal RAIM availability results for APVI and APVII respectively. The APVI result is largely the same as that for the current system (Figure 2). The main reasons for this are that the satellite geometry is the same and with a horizontal alarm limit of 0.3 nmi (555 m), the better UERE budget for Block IIF satellites makes a very small impact on availability. The APVII result shows an improvement on the current system (Figure 3) particularly in the mid to higher latitude areas.

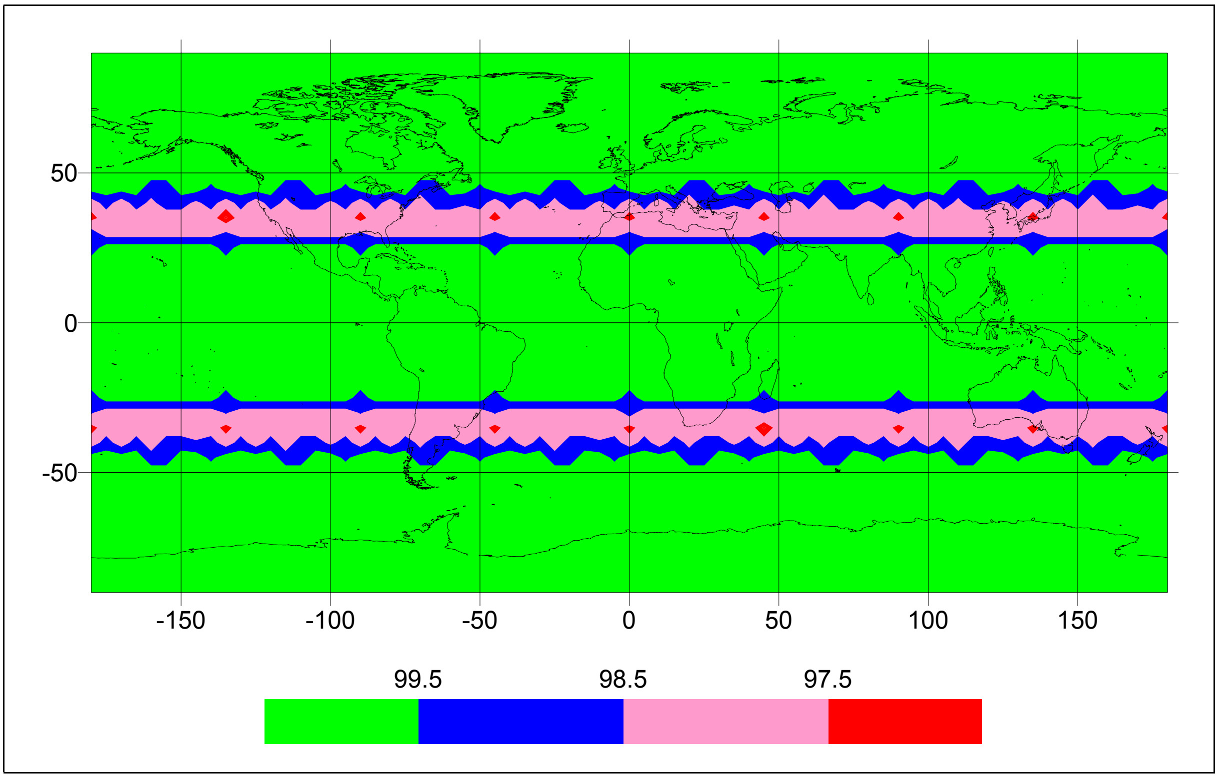

Figure 6 APVI Modernised Horizontal RAIM Availability

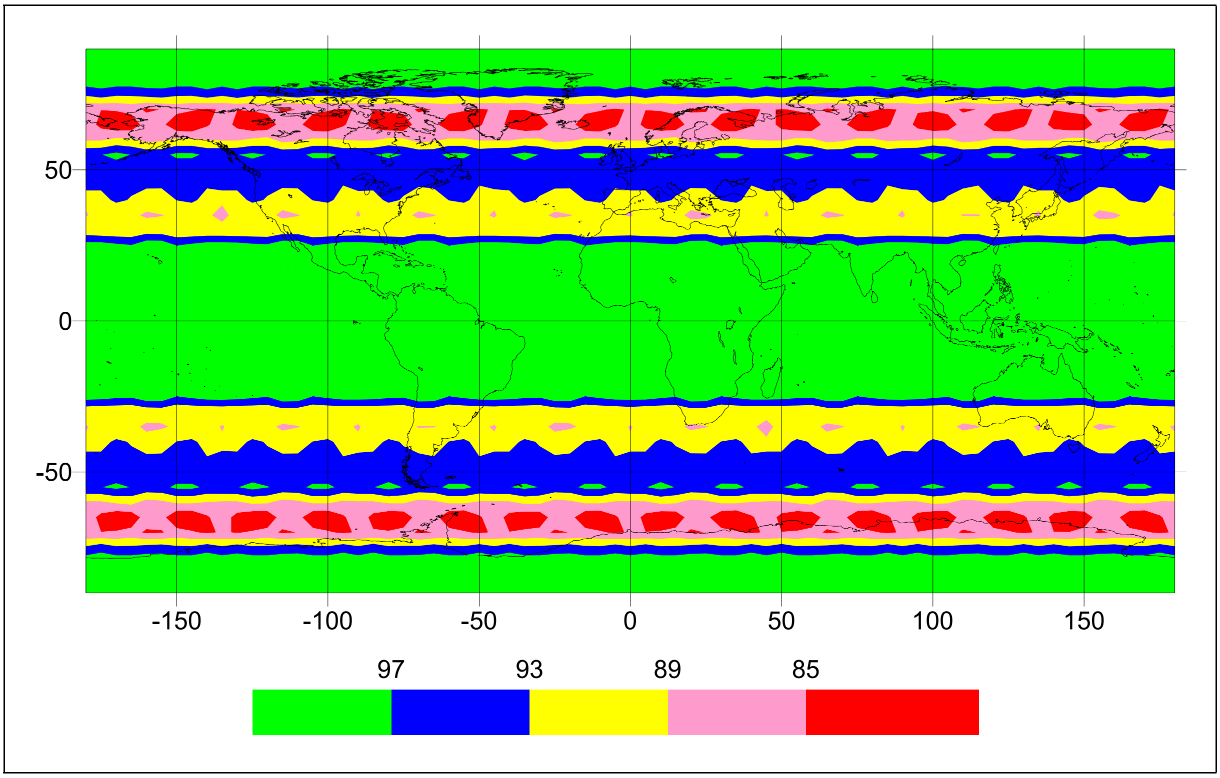

Figure 7 APVII Modernised Horizontal RAIM Availability

Figures 8 and 9 show the corresponding results for vertical RAIM availability. The APVI result is largely the same as the current system. The APVII result shows improvement in the equatorial and mid latitude areas, compared to the current system (Figure 5).

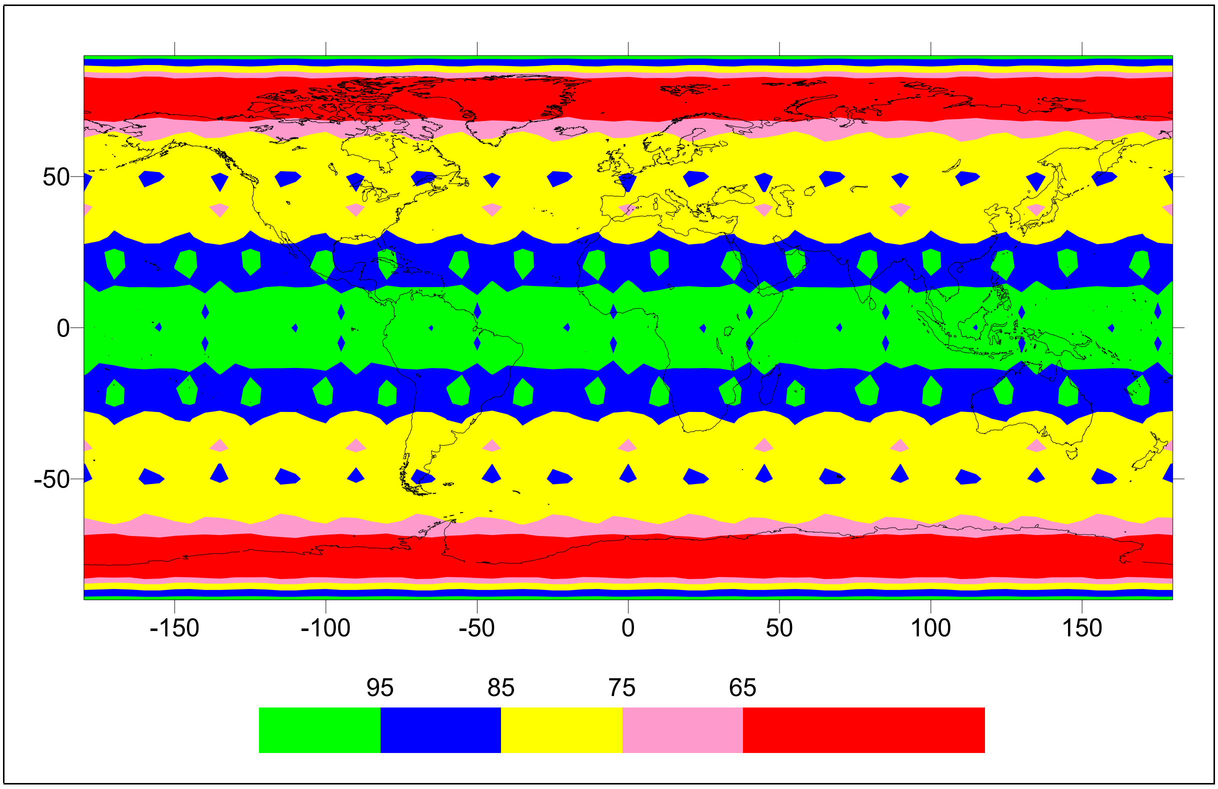

Figure 8 APVI Modernised Vertical RAIM Availability

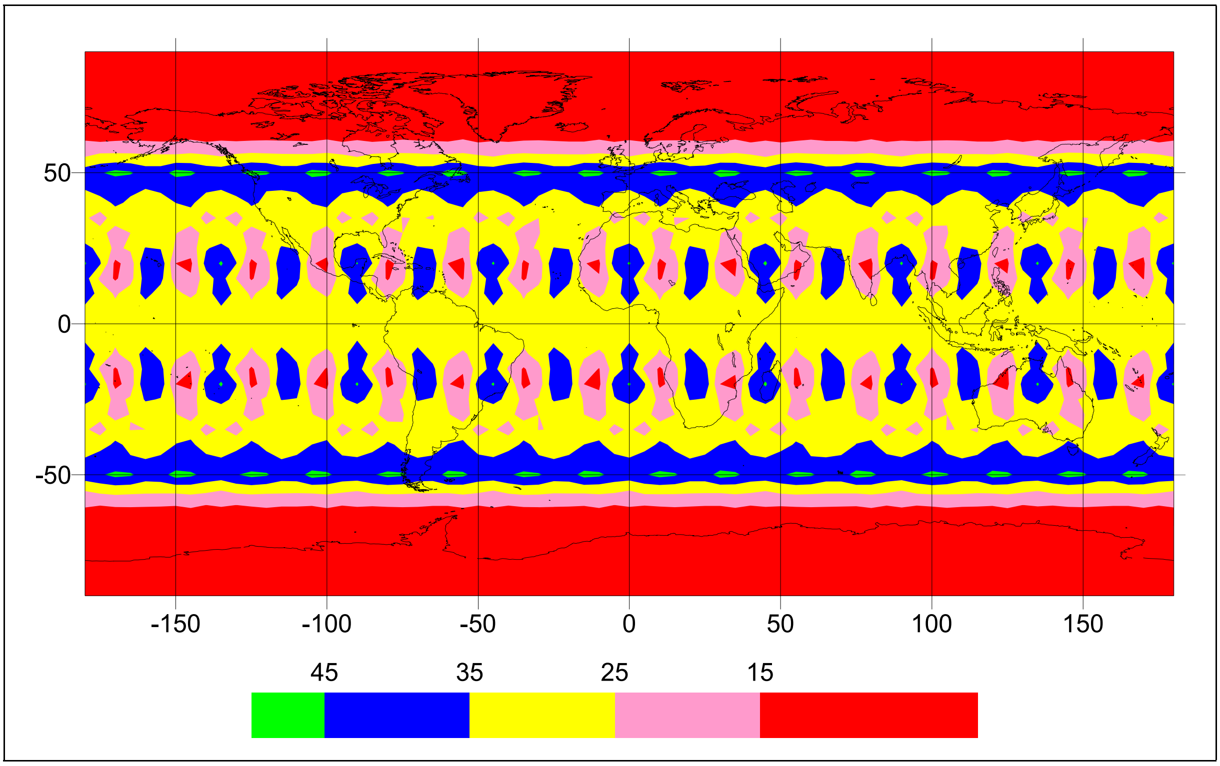

Figure 9 APVII Modernised Vertical RAIM Availability

5.1.6 Summary

An integrity impact assessment of the short to medium term GPS modernisation activities has been carried out and presented. It has been shown that a certain level of improvement is to be expected, although this will still not be adequate for the navigation requirements of aviation.

5.2 Long term modernisation initiatives

5.2.1 GPS III Program

The short to medium term modernisation activities should carry the constellation through approximately 2010. To meet military and civil requirements through 2030, the Interagency GPS Executive Board (IGEB) has accepted a DOD recommendation to design a new generation of satellites (Block III) and associated ground control network for use beyond 2010. The objective of the GPS III initiative is to deliver a GPS architecture that will satisfy current and evolving civilian needs, in particular the RNP for air navigation. It will preserve and build on the successes of GPS by creating a new architecture based on defined operational requirements (Lee **et al.**, 2001). The system will deliver enhanced position, velocity, and timing (PVT) signals, and related services to meet the requirements of the next generation of military and civil GPS users.

The GPS III program includes an integrated space segment (SS) and control segment (CS) system that incorporates the Nuclear Detonation Detection System (NUDET) and defines the Signal-in-Space (SIS) to User Equipment (UE) interface. The system should provide a best value solution with the flexibility to anticipate and respond to future military and civilian needs, and should facilitate the incorporation of additional mission capabilities (i.e. Blue Force Tracking (BFT), Search and Rescue (SAR) missions, etc.). The security infrastructure should provide user access to and protection of the entire system.

The first GPS III satellite is to be launched in 2009, with an eventual 30-satellite constellation to serve users until around 2030 (Lee **et al.**, 2001). The FOC is estimated to be achieved around 2020. The program is currently in the requirements definition and preliminary design phases. The key stages of development are given below.

- User and system requirements definition (2002-2004).
- Architecture definition (2004-2006).
- Production and Deployment (2007 onwards).

A key element of the programme is to address the RNP for aviation and how this is to be achieved, particularly the integrity requirements. The expectation is that the system will incorporate an independent external network to monitor the signal-in-space (SIS) and notify users of any significant anomaly with the required time-to-alerts and within the specified probabilities of risk. Of course for safety reasons, it would still be necessary to have a RAIM capability within the receiver to protect against those anomalies, which may not be captured by the external network.

5.3 Summary

This Section has presented and analysed the impact of planned GPS modernisation on integrity monitoring. The activities have been analysed under the two categories of short to medium term (to 2010) and long term (to 2020). In the short to medium term it has been shown that a certain level of improvement is to be expected, although this will still not be adequate for the required navigation performance for aviation.

In the long term a key element of the proposed GPS III programme is to address the RNP for aviation and how this is to be achieved, particularly the integrity requirements. The expectation is that the system will incorporate an independent external network to monitor the signal-in-space (SIS) and notify users of any significant anomaly with the required time-to-alerts and within the specified probabilities of risk. For safety reasons, it would still be necessary to have a RAIM capability within the receiver to protect against those anomalies, which may not be captured by the external network.

6 GPS augmentation

The previous sections have shown that the current mechanisms adopted for monitoring the integrity of GPS are not adequate for the required navigation performance for all phases of flight. This justifies the need for augmentation of the current approaches to support integrity monitoring. This section now looks at the options available under the two main categories, GNSS1 and GNSS2.

6.1 GNSS1

The first generation global navigation satellite system (GNSS1) has been defined by the ICAO/GNSS panel to include existing space based navigation systems, GPS and Russia's GLONASS and any other augmentation systems required to enable the required navigation performance (RNP) to be achieved. GNSS1 therefore deals with the performance limitations of the existing systems.

There are a number of options available for improving the performance of the existing systems including satellite-based augmentation system (SBAS), ground based augmentation system (GBAS), and aircraft based augmentation system (ABAS). The US FAA has proposed to use GPS based navigation for the various phases of flight as shown in Table 13 below.

Table 13 GPS for various phases of flight

Phase of Flight		Integrity	Availability	Accuracy
En Route	Oceanic	GPS + ABAS (RAIM/AAIM)	▨	▨
	Domestic	SBAS desirable		▨
Approach and Landing	Non-Precision Approaches			▨
	CAT I Precision Approaches	SBAS or GBAS	🟩	🟩
	CAT II/III Precision Approaches and Surface Movement	GBAS	🟥	🟥
Surface	Ground Movement	SBAS or GBAS	🟩	🟩

Each of the GNSS1 augmentation approaches are now discussed in turn.

6.1.1 Satellite based augmentation systems

In SBAS, a wide coverage augmentation system is adopted in which the user receives augmentation information from a satellite-based transmitter. The current approach employs an independent network of tracking and integrity monitoring stations used to acquire satellite data. The data is then used to determine the information required to improve performance.

SBAS improves accuracy by broadcasting corrections for navigation errors, service availability by providing extra ranging data, and **integrity** by the near-real time broadcast (within the time-to-alert requirement) of the system/satellite health status through a dedicated GNSS integrity channel (GIC). Currently there are three space based augmentation systems under development, the European Geostationary Navigation Overlay Service (EGNOS), the US Wide Area Augmentation System (WAAS) and the Japanese MTSAT (Multi-functional Transport SATellite) satellite-based augmentation system (MSAS). EGNOS and WAAS are currently in the trials phase. As indicated in Table 13 above, satellite-based augmentation systems are being developed to enable the RNP for CAT I precision approach to be achieved.

EGNOS is expected to come into operation in 2003. The WAAS programme has been delayed as a result of funding cuts by the US government and uncertainties due to a number of issues including concern about ‘sole means navigation’, viability as a business and delays in software specification. Recent trials have demonstrated the accuracy provided to be within the specified vertical requirement for CAT I. However, the integrity requirement is still not fully satisfied. This has led to a requirement for updates in the modelling algorithms and software resulting in further delays (Abousalem **et al.**, 2000). WAAS is expected to achieve initial operational status in 2003 with full operation capability in 2009.

6.1.2 Ground based augmentation system

In GBAS the user receives augmentation information from a ground-based transmitter. As stated above, the use of SBAS should allow the improvement in performance of GPS (and GLONASS) to approach the RNP for CAT I precision approach. In order to enable up to CAT III, currently obtained with instrument landing system (ILS) and microwave landing system (MLS), the use of GBAS is necessary.

In GBAS local area differential corrections are transmitted via a ground-based transmitter to improve accuracy. The basic observable used is the code phase where differential corrections enable positioning accuracy at the metre level. Higher accuracy (cm level) could be obtained by the transmission and application of differential corrections to the carrier phase observable. However, this currently has a lower level of reliability than code phase based GBAS.

Service availability can be improved by the installation and operation of pseudolites (effectively GPS satellites on the ground). **Integrity** is improved by the near-real time transmission (within the time-to-alert requirement) of system/satellite health status (Bartone and Kiran, 2000).

6.1.3 Aircraft based augmentation system

This approach augments and/or integrates the information obtained from the other GNSS elements with information available on board the aircraft. It should therefore improve both availability and integrity.

The basic approach used for integrity monitoring at the user level (e.g. on board the aircraft) is the receiver autonomous integrity monitoring (RAIM). RAIM has been addressed in some detail in previous chapters. Although simple to implement, it has the limitation of availability due to its requirement for at least 5 satellites for failure detection and 6 for exclusion.

Improvement on the basic RAIM performance can be obtained by the application of the concept of aircraft autonomous integrity monitoring (AAIM). AAIM uses data from satellite based navigation systems and information traditionally available on board the aircraft. Such traditional navigation data sources include radio navigation systems (DME, VOR, LORAN-C, Omega), precise clock, radar, inertial navigation system (INS) and aerodynamic (and thermodynamic) sensors for generating air data (e.g. air speed and altitude). Improvement can be achieved through comparing GPS derived positions with those from the other independent sensor/systems. In this case the systematic errors of the independent sensors/systems (e.g. inertial sensor drifts) are calibrated by GPS when RAIM is available. Alternatively, the raw data from the other sensors/systems could be treated as additional to GPS data and used for position solution. In this case RAIM algorithms are applied with the extra data expected to improve RAIM availability. In both cases it is important that the potential failure modes and error sources associated with the different systems are clearly understood and taken into account in the integrity monitoring capability analysis.

The integration of GPS with, for example, the barometer and precise clock are relatively simple. These systems simply provide new measurements and the RAIM algorithms can be applied directly to check the integrity of the systems, with suitable weights applied to data from the different systems. The barometer measures air pressure rather than the geometric altitude directly. The airborne barometer errors can be calibrated either with GPS or a local barometric setting. Studies have shown that barometer aiding improves the mean availability of autonomous integrity monitoring over GPS alone to nearly 100% for oceanic and en route phases of flight. NPA availability is also improved to about 90% well below the required level for this phase of flight (Lee, 1992).

Integration of GPS with the data from the other traditional navigation systems is more complex. Firstly the locations of the ground radio transmitter stations should be determined in WGS84. This can be realised either by carrying out a ground survey or by the approach proposed by Ashkenazi **et al** (1995) based on an aircraft trajectory from GPS data. The failure modes and associated errors of the systems involved also need to be identified and modelled. For example in the case of DME, the errors considered are due to inaccuracy of the ground station coordinates, incorrect calibration of the built-in transponder delay (bias), the range dependent offset from a varying signal-to-noise ratio in the ground based and airborne elements (scale error), and atmospheric refraction. In the case of LORAN-C, the major error source is due to propagation effects. Studies on system integrity of combining GPS data with LORAN-C for non-precision approach, have shown an improvement on GPS from 97.335% to 99.982% for failure detection (FD) with a 24-satellite constellation. The corresponding figures for failure detection and isolation (FDI) are 46.2% and 97.72% (Weitzen **et al.**, 1996). Hence, although there is significant improvement, GPS augmented with LORAN-C still falls short of meeting the navigation integrity requirement for NPA.

Inertial navigation has been widely used in many military vehicles and nearly all long distance civilian aircraft for navigation purposes for many years. An inertial navigation system (INS) derives its position through the double integration of measured accelerations along specific directions. It is subject to a drift in position accuracy caused by various instrument error sources, including the gyroscope (random walk, bias, scale factor and misalignment), and accelerometer (bias, scale factor and misalignment). GPS and INS have complementary characteristics making their integration very useful. INS has almost no high frequency noise, but it can have large low frequency errors (biases). In other words, it is a short-term very precise measurement source with poor long-term stability. GPS on the other hand, has high frequency noise but good long-term accuracy. The integrity of the integrated system is improved in two ways. The sensor errors of the INS are calibrated by the GPS measurements through a Kalman filter. The GPS measurement errors, on the other hand can be detected by comparing with the calibrated INS positions.

Studies carried out have shown that integrated GPS/INS systems have the potential to meet the RNP up to non-precision approach (NPA) phase of flight. Diesel and Dunn

(1996) reported near 100% availability of fault detection and exclusion for non-precision approach with a 24-satellite constellation. This potential was recognised by the RTCA SC-159, which formed a GPS/inertial working group in 1997 to develop Minimum Operational Performance Standards (MOPS) for requirements and test procedures for a tightly integrated GPS/inertial system to be used for en route, terminal and non-precision approach phases of flight. This exercise is currently on-going. Further studies by Lee and O'Laughlin (1999) have investigated the capability of the integrated GPS/inertial system to detect failures that cause slowly growing errors (note that failures that cause sudden errors can be easily detected by the inertial mechanism). The results based on two approaches for integrity calculations have not been conclusive and further research has been suggested.

6.2 GNSS2

The second-generation global navigation satellite system (GNSS2) is to be developed to address both institutional and performance limitations of the existing GPS and GLONASS. The Galileo system is currently under development as a global, satellite based navigation system to support **multi-modal** transport navigation requirements and many other applications that require spatial and/or temporal information to users equipped with suitable Galileo receivers. It will be compatible and interoperable with GPS, GLONASS, SBAS and GBAS currently under development. The system, which is expected to achieve **full operational capability** (FOC) by the year 2008 will be under European civil control and open to international participation. The system will consist of global, regional and local components designed to satisfy the requirements of many users including civil aviation (Tytgat and Campagne, 2000).

Since Galileo is to be fully compatible and interoperable with GPS, a RAIM availability analysis has been carried out for the combined use of data from Galileo and GPS. The analysis has taken into account potential system failure modes based on GPS, extrapolation of GPS based on modernisation activities presented in Section 5 and the Galileo architecture (navigation error budget and satellite constellation) as proposed for FOC in 2008.

The results of the analysis of the capability to perform RAIM computation are shown in Figures 10 and 11 for APVI horizontal and vertical RAIM availability respectively. The corresponding results for APVII are shown in Figures 12 and 13.

It can be seen that the availability of RAIM for APVI (horizontal and vertical) and APVII (horizontal) nears 100% (within the spatial and temporal sampling limits used). The vertical RAIM availability for APVII nears 100% in most places with the exception of the higher and lower latitude areas experiencing availability at the 96% level.

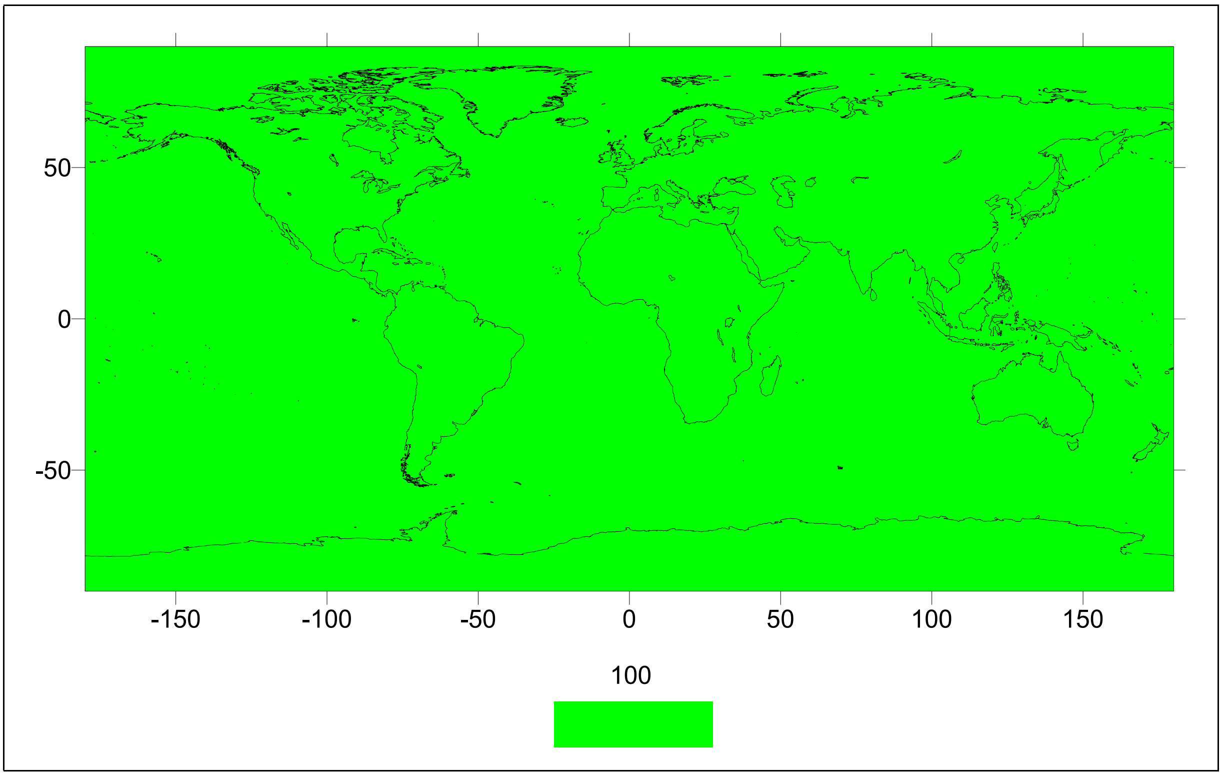

Figure 10 APVI GPS+GALILEO Horizontal RAIM Availability

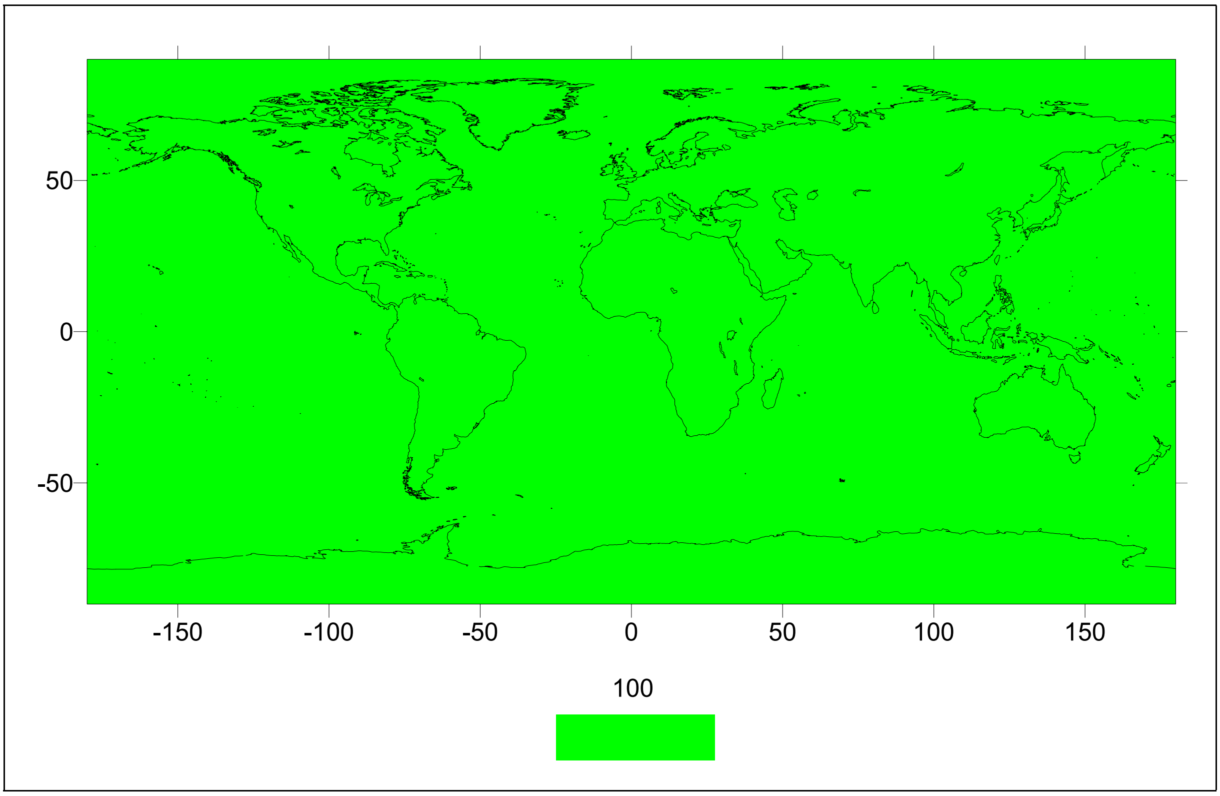

Figure 11 APVI GPS+GALILEO Vertical RAIM Availability

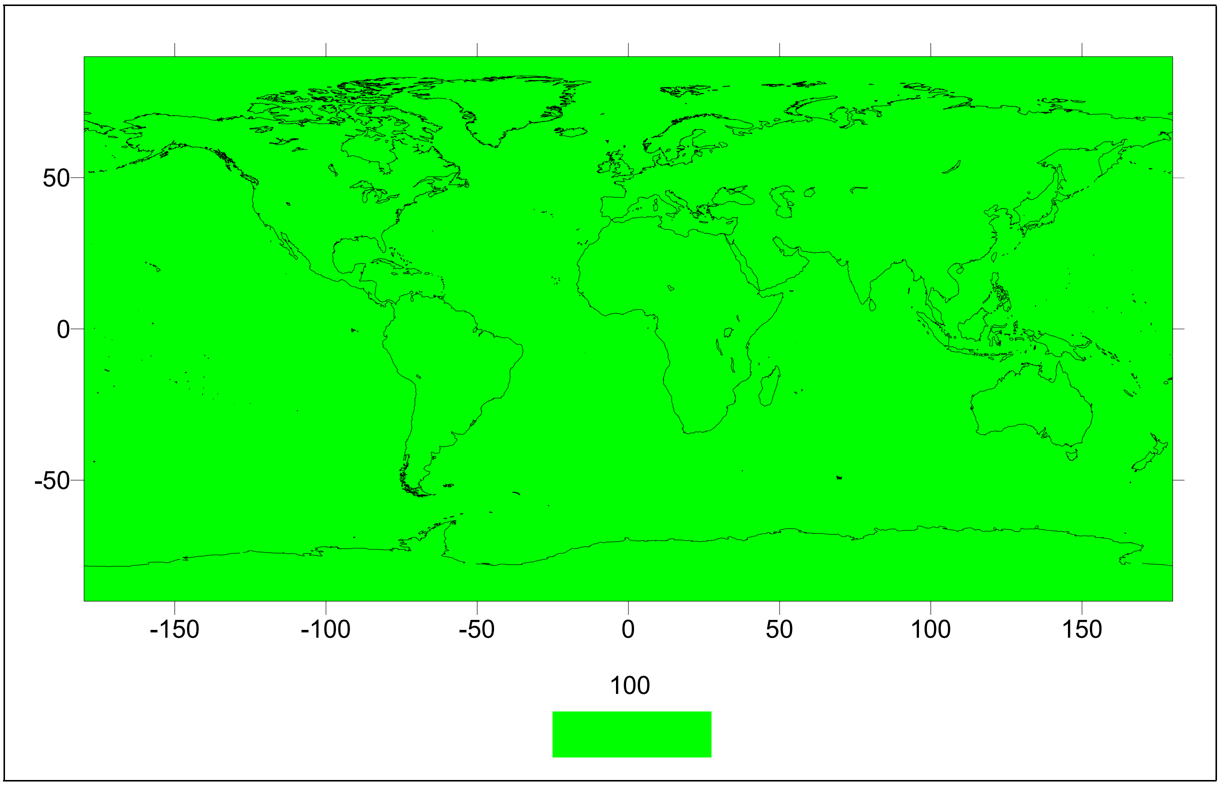

Figure 12 APVII GPS+GALILEO Horizontal RAIM Availability

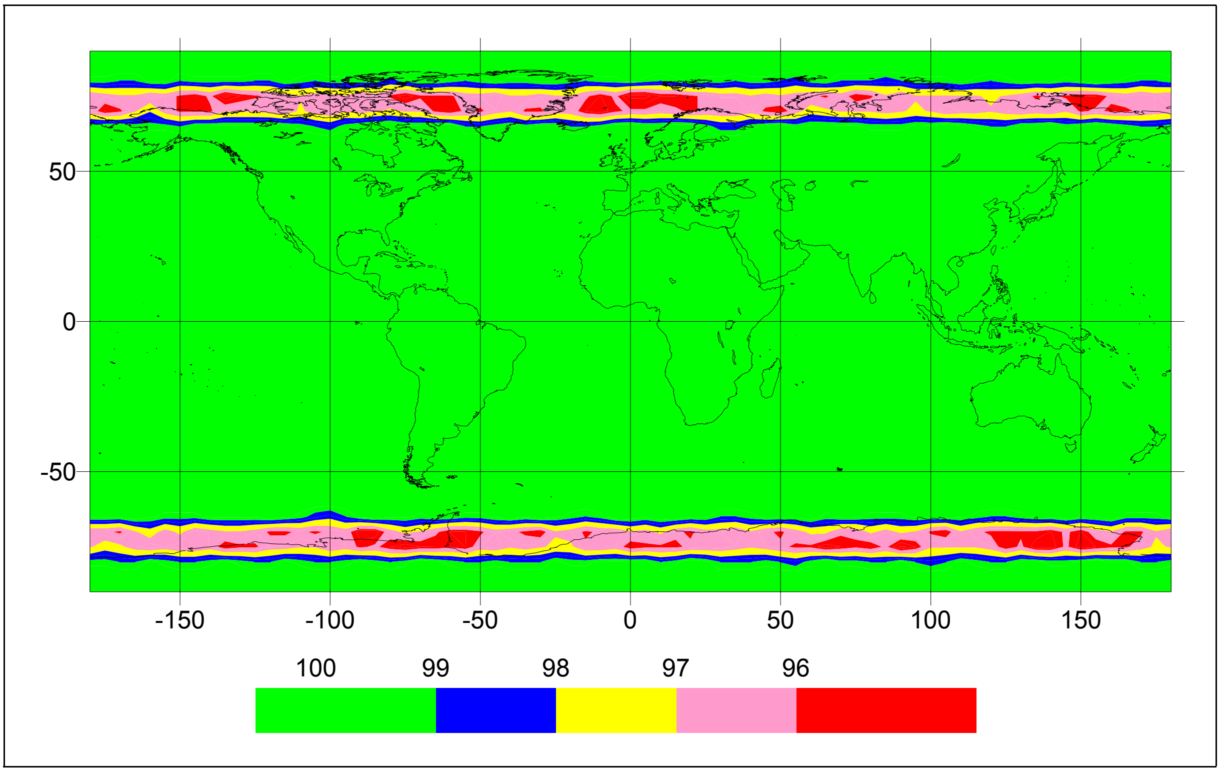

Figure 13 APVII GPS+GALILEO Vertical RAIM Availability

6.3 Summary

This Section has presented the various augmentation mechanisms that could be used to support the integrity requirements for civil aviation. GNSS1 based approaches including satellite-based augmentation system (SBAS), ground-based augmentation system (GBAS) and aircraft based augmentation system (ABAS) have been identified and their proposed role in the various phases of flight discussed. SBAS and GBAS systems should enable precision approach and landing to be achieved. With respect to ABAS, the integration of GPS with barometric aiding has the potential to achieve the integrity requirements for oceanic and en route phases of flight. GPS and INS integration appears to have the potential to satisfy the required navigation performance for up to non-precision approach phase of flight. However, so far research on this has not been entirely conclusive and further research is required.

The potential of the combined use of data from GPS and second-generation global navigation satellite systems (GNSS), in particular has been analysed through a RAIM availability analysis. It has been shown that the availability of RAIM for APVI (horizontal and vertical) and APVII (horizontal) nears 100%. The vertical RAIM availability for APVII is close to 100% in most places with the exception of the higher and lower latitude areas experiencing availability at the 96% level.

7 Conclusions and Recommendations

7.1 Conclusions

The study was carried out to investigate the level of safety as measured by integrity (i.e. trustworthiness), afforded by GPS as a source of navigation data for civil aircraft. The main objective was to investigate potential cases of non-integrity (i.e. failures) that could result in safety risks, their causes and mitigation techniques.

The study has shown that GPS is susceptible to different types of failures with potential impacts on safety if not identified and reported within specified time periods. The current system level and user level monitoring mechanisms have been shown to be inadequate for providing the necessary integrity monitoring capability. Different augmentation approaches have been presented based on the concepts of GNSS1 (ground-based, aircraft-based and space-based augmentation systems) and GNSS2 (stand-alone navigation systems such as Galileo). These have been shown to have the potential to satisfy the RNP for all phases of flight. The systems are currently under development and further research is required before they can be used for civil air navigation. It should be noted that there are plans to modernise GPS (the so-called GPS III programme) to support the navigation requirements for many more applications including civil aviation. The system is expected to be operational in 2020.

7.2 Recommendations

An important objective of the CAA regulatory process should be to put in place a method to deal with certification requests for systems and process to be used in safety critical applications. Such a process requires a credible qualitative and quantitative verification plan and methodology to independently assess whether proposed systems and services perform as designed and within the operational performance requirements. In order for this to be done, the ATS requirements and architecture should be understood to the lowest (elemental) level together with the corresponding failure modes and rates. From this, a hazard analysis can be carried out for the entire service. This study has been a contribution to this with respect to the navigation element.

The study presented here has been based on an existing body of research reports on GPS integrity and quantitative analyses of the capability to carry out RAIM calculations (i.e. RAIM availability). The failure probabilities were based on reported failures of GPS satellites as observed in operation over a number of years. Whereas the analysis of the capability to carry out a RAIM calculation is important particularly as a prediction tool, it is vital to carry out analysis of actual RAIM computations using raw (or simulated) navigation data. This requires further analysis of all the failure modes to determine failure rates (probabilities). Figure 14 below shows a generic integrity risk tree for an air navigation system. The failure mode analysis should consider all the relevant elements as shown in Figure 14. With this in mind it is suggested that further analysis should proceed as given below.

a) Consolidation and bounding of possible system and operational failure modes including probabilities of failure.

b) Consolidation and bounding of the effects of different user equipment on incident signal failures and also user equipment performance levels and failures.

c) Definition of the necessary test and simulation parameters, e.g. area of operation.

d) Execution of simulations to determine if the requirements of the phase of flight in question can be achieved based on simulated range measurements as opposed to availability analysis.

e) Determination of mitigation strategies and repetition of steps 1 to 4 for those strategies involving augmentation with other sensors and systems.

The results of the above exercise should form an essential input into the specification of a verification process for GPS-based navigation systems. Similar exercises should then be carried out for the remaining elements of an ATS in order that an overall safety case can be determined.

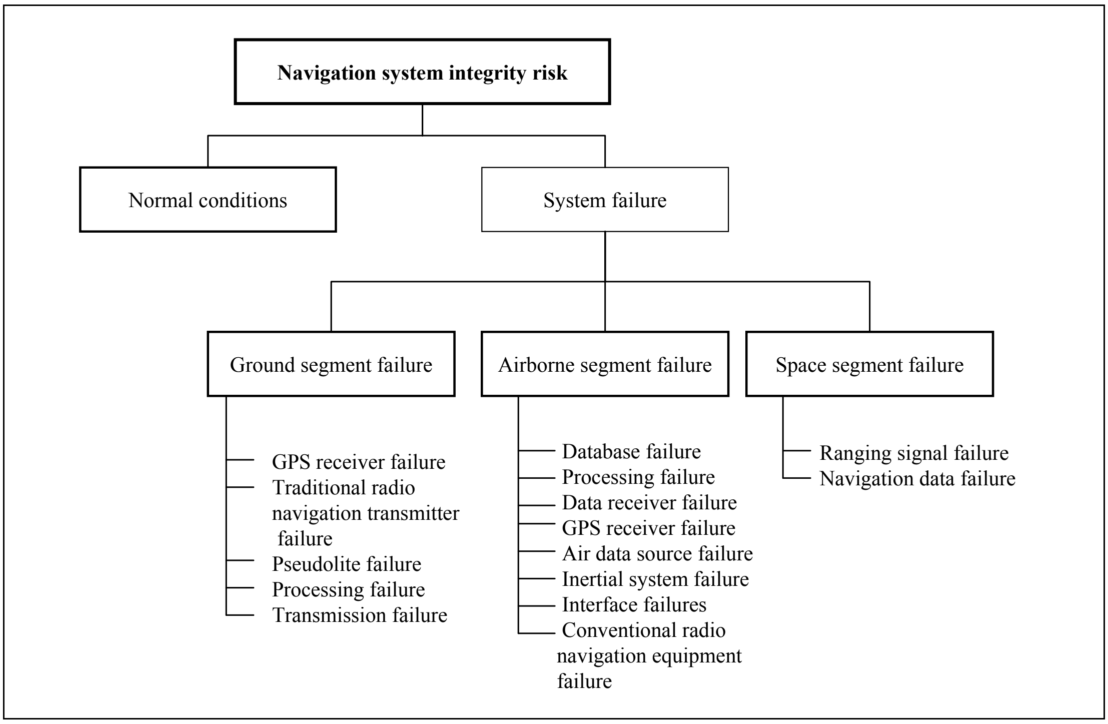

Figure 14 Generic integrity risk tree for an air navigation system

Appendix A References and Applicable Documents

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Appendix B Glossary

AAIM	Aircraft Autonomous Integrity Monitoring
ABAS	Aircraft-Based Augmentation System.
AII	Accuracy Improvement Initiative
ATC	Air Traffic Control
BFT	Blue Force Tracking
CAA	Civil Aviation Authority
C/A	Course Acquisition
CAT	Category
CNS/ATM	Communication, Surveillance and Navigation / Air Traffic Management
CTS	Centre for Transport Studies
DOP	Dilution of Precision
EAROM	Electrically-Alterable, Read-Only Memory
EGNOS	European Geostationary Navigation Overlay Service
FAA	Federal Aviation Administration
FD	Failure Detection
FDI	Failure Detection and Isolation.
FOC	Full Operational Capability
FRP	Federal Radionavigation Plan
GBAS	Ground Based Augmentation System
GCOST	GNSS Constellation Simulation Tool
GDAP	GNSS Data Analysis Package
GIS	GNSS Integrity Channel
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAL	Horizontal Alarm Limit
HDOP	Horizontal Dilution of Precision
HMI	Hazardously Misleading Information
ICAO	International Civil Aviation Organisation
ICD	Interface Control Document
ICON	IC Consultants Limited

IGEB	Interagency GPS Executive Board
ILS	Instrument Landing System
INS	Inertial Navigation System
IODE	Issue of Data Ephemeris
IODC	Issue of Data Clock
ISN	Institute of Satellite Navigation
JTIDS	Joint Tactical Information Distribution Service
KO	Kick Off
LCGR	London Centre for GNSS Research
MCS	Master Control Station
MD	Man Day
MLS	Microwave Landing System
MOPS	Minimum Operational Performance Standard
MSAS	MTSAT Satellite-based Augmentation System
MTSAT	Multi-functional Transport Satellite
NANU	Notice Advisory to Navstar Users
NAVWAR	Navigation Warfare
NIMA	National Imagery Mapping Agency (NIMA)
NPA	Non Precision Approach
NSE	Navigation System Error
NUDET	Nuclear Detonation Detection System
OCS	Operational Control Segment
PA	Precision Approach
PDD	Presidential Decision Directive
PRN	Pseudorandom noise
RAIM	Receiver Autonomous Integrity Monitoring
RNP	Required Navigation Performance
PPS	Precise Positioning Service
PVT	Position, Velocity and Time
RF	Radio Frequency
RTCA	Radio Technical Commission for Aviation
SA	Selective Availability
SAR	Search and Rescue

SARPs	Standards and Recommended Practices
SBAS	Space Based Augmentation System
SIS	Signal in Space
SRG	Safety Regulation Group
SPS	Standard Positioning Service
SS	Space Segment
SV	Space Vehicle
TKS	Time Keeping System
UE	User Equipment
VAL	Vertical Alarm Limit
WDM	Watch Dog Monitor
WGS84	World Geodetic System 1984
Y2K	Year 2000