INSPIRe

D2.1 – Technical Report of Developments and Test of GPS M(G)RAIM

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1 INTRODUCTION

1.1 Purpose

This document is deliverable D2.1 of the INSPIRe project, titled 'Technical report of developments and test of GPS M(G)RAIM'. This deliverable document is one of the main outputs of WP2 and the purpose is to report on the activities that have been completed within WP2, including:

- Review of the state-of-the-art of algorithms for integrity in the maritime domain
- Overall description of the chosen M(G)RAIM algorithms
- Outcomes of testing of GPS M(G)RAIM algorithms
- Description of the suitability and shortcomings of the algorithms for use in the maritime environment, highlighting any areas that need improvement
- Assessment of the need for a maritime-specific EGNOS message to support MRAIM
- Preliminary definition of system-level integrity data requirements for a maritime-specific message

1.2 Scope

Following the introduction to the document presented in Section 1, the layout of the remainder of the document is as follows:

- **Section 2** contains a list of applicable and reference documents
- **Section 3** presents the state-of-the-art review
- **Section 4** describes the high-level algorithm design
- **Section 5** presents the description of testing
- **Section 6** summarises the suitability of the algorithm and highlights any further areas for investigation
- **Section 7** contains an assessment of the need for a maritime specific EGNOS message and a discussion on the preliminary definition of requirements for a maritime specific message

1.3 Definitions and Acronyms

1.3.1 Definitions

Concepts and terms used in this document and need defining are included in the following table:

Table 1-1 Definitions

Concept / Term	Definition
MG-RAIM	Maritime General-RAIM: is a chi-squared fault-detection process with simple geometric screening rules to ensure safety
MRAIM	Maritime RAIM: is a maritime-specific implementation of the aviation ARAIM concept and performs a multiple-hypothesis solution-separation process, then computes a protection level and iteratively optimises this PL through re-allocation of integrity risk

1.3.2 Acronyms

Acronyms used in this document and need defining are included in the following table:

Table 1-2 Acronyms

Acronym	Definition
AL	Alert Limits
ARAIM	Advanced Receiver Autonomous Integrity Monitoring

CDF	Cumulative distribution function
DFMC	Dual Frequency Multiconstellation
DGNSS	Differential GNSS
DGPS	Differential GPS
DOP	Dilution of Precision
ECAC	European Civil Aviation Conference
EGNOS	European Geostationary Navigation Overlay Service
ESA	European Space Agency
FD	Fault Detection
FDE	Fault Detection and Exclusion
GBAS	Ground-Based Augmentation System
GEAS	GNSS Evolutionary Architecture Study
GLONASS	GLObal NAvigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRAD	GLA Research and Development
GSA	European GNSS Agency
HAL	Horizontal alarm Limit
HDOP	Horizontal Dilution of Precision
HMI	Hazardous Misleading Information
HPE	Horizontal Position Error
HPL	Horizontal Protection Level
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
ICAO	International Civil Aviation Organisation
IEC	International Electrotechnical Commission
INSPIRe	Integrated Navigation System-of-Systems PNT Integrity for Resilience
IMO	International Maritime Organisation
IR	Integrity Risk
ISM	Integrity Support Message
LPV	Localizer Performance with Vertical guidance
MHSS	Multiple Hypothesis Solution Separation
MOPS	Minimum Operational Performance Standards
MGRAIM	Maritime General RAIM
MRAIM	Maritime RAIM
MSC	Maritime Safety Committee
MSI	Maritime Safety Information
MSR	Multi-system shipborne receiver
N/A	Not Applicable
NLOS	Non-Line of sight
NPA	Non-Precision Approach
PFA	Probability of False Alarm
PL	Protection Level
PHMI	Probability of Hazardously Misleading Information
PMD	Probability of Miss detection
PNT	Positioning Navigation and Timing
PVT	Position, Velocity and Time
RAIM	Receiver Autonomous Integrity Monitoring
RTCA	Radio Technical Commission for Aeronautics
RTK	Real-time kinematic positioning
SARPS	Standards and Recommended Practices
SBAS	Satellite Based Augmentation System
SIS	Signal in Space
SOLAS	Safety at Life at Sea
TBC	To Be Confirmed
TTA	Time to Arrival
VAL	Vertical alarm Limit
VHF	Very High Frequency

2 REFERENCES

2.1 Applicable Documents

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.x]:

Table 2-1 Applicable Documents

Ref.	Title	Code	Version	Date
[AD.1]	INSPIRe Technical Proposal, Taylor Airey	T-062-001-02 Part 1	-	June 2022
[AD.2]	INSPIRe Management Proposal, Taylor Airey	T-062-001-02 Part 2	-	June 2022
[AD.3]	INSPIRe Proposal GMV	GMV 10842/21	V2/21	

2.2 Reference Documents

Although not part of this document, the following documents amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.x]:

Table 2-2 Reference Documents

Ref.	Title	Code	Version	Date
[RD.1]	ICAO, Annex 10, Aeronautical Telecommunications, Volume 1 (Radio Navigation Aids), Amendment 86, effective 17 November 2011. GNSS standards and recommended practices (SARPs) are contained in Section 3.7 and subsections, Appendix B, and Attachment D.	-	6th	07/2006
[RD.2]	"High integrity for GNSS applications" Marco Caparole. SOGEI Workshop GNSS technology advances in a multi-constellation framework	-	-	26/09/2014
[RD.3]	GNSS Measurements Modelling from Navipedia website http://www.navipedia.net/index.php/GNSS_Measurements_Modelling	-	-	01/2017
[RD.4]	Minimum Operational Performance Standards (MOPS) for Global Positioning System/Satellite-Based Augmentation System Airborne Equipment	RTCA DO-229E		11/06/2020
[RD.5]	EGNOS SoL Service Definition Document	EGNOS-SoL-SDD	3.4	2021
[RD.6]	"Beyond accuracy – the integrity era" Allison Kealy. SBAS 2015 workshop sponsored by Thales Australia	-	-	2015
[RD.7]	"Integrity" from Navipedia website http://www.navipedia.net/index.php/Integrity	-	-	-
[RD.8]	SBAS Fundamentals https://gssc.esa.int/navipedia/index.php/SBAS_Fundamentals	-	-	Accessed 3/10/2022
[RD.9]	GBAS Fundamentals https://gssc.esa.int/navipedia/index.php/GBAS_Fundamentals	-	-	Accessed 3/10/2022

[RD.10]	EUSPA EGNOS APV-I and LPV-200 Availability Map (https://egnos-user-support.essp-sas.eu/new_egnos_ops/maps_apv1 / https://egnos-user-support.essp-sas.eu/new_egnos_ops/lpv200_maps)	-	-	Accessed 3/10/2022
[RD.11]	GNSS Evolutionary Architecture Study. Phase I – Panel Report. February 2008	-	-	2008
[RD.12]	Channel Characterisation for Spread Spectrum Satellite Communication, Jahn, A., Bischil, H and Heib, G.	IEEE 4th International Symposium		09/1996
[RD.13]	Combined Performance for Open GPS/Galileo Receivers EU-US Cooperation on Satellite Navigtion Working Group C		Final	19/07/2010
[RD.14]	Minimum Operational Performance Standards (MOPS) for Global Positioning System/Aircraft Based Augmentation System Airborne Equipment	RTCA DO-316		14/04/2009
[RD.15]	Advanced RAIM Reference Airborne Algorithm Description Document	ARAIM ADD	V4.0	02/2022
[RD.16]	GNSS Evolutionary Architecture Study. Phase II – Panel Report. February 2010	-	-	2010
[RD.17]	Interim Report. EU-U.S. Cooperation on Satellite Navigation Working Group C, ARAIM Technical Subgroup. Date: December 1th, 2012, available at the following address: https://www.gps.gov/policy/cooperation/europe/2013/working-group-c/ARAIM-report-1.0.pdf	-	-	2012
[RD.18]	Milestone 2 Report. EU-U.S. Cooperation on Satellite Navigation Working Group C, ARAIM Technical Subgroup. Date: February 11th, 2015, available at the following address: https://ec.europa.eu/docsroom/documents/9567/attachments/1/translations/en/renditions/pdf	-	-	2015
[RD.19]	Milestone 3 Report. EU-U.S. Cooperation on Satellite Navigation Working Group C, ARAIM Technical Subgroup. Date: February 25th, 2016, available at the following address: https://ec.europa.eu/newsroom/growth/redirection/item/48690	-	-	2016
[RD.20]	S. Paternostro, T. Moore, C. Hill, J. Atkin, G. De Maere and H. P. Morvan, "Examples of user algorithms implementing ARAIM techniques for integrity performance prediction, procedures development and pre-flight operations," 2016 8th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC) , 2016, pp. 1-15, doi: 10.1109/NAVITEC.2016.7849330.	-	-	2016
[RD.21]	J. Blanch, T. Walter, P. Enge, Y. Lee, B. Pervan and A. Spletter. Advanced RAIM User Algorithm Description: Integrity Support Message Processing Fault Detection Exclusion and Protection Level Calculation", Proceedings of ION GNSS, 2012, pp. 2828-2849	-	-	09/2012
[RD.22]	Zabalegui, Paul & De Miguel, Gorka & Perez, Alejandro & Mendizabal, Jaizki & Goya, Jon & Adin, Inigo. (2020). A Review of the Evolution of the Integrity Methods Applied in GNSS. IEEE Access. PP. 1-1.	-	-	03/2020

[RD.23]	GPS Integrity and Potential Impact on Aviation Safety. Civil Aviation Authority 2004	CAA PAPER 2003/9	-	April 2004
[RD.24]	A.915(22) Revised Maritime Policy and Requirements for a Future Global Navigation Satellite System (GNSS)	IMO/A.915 (22)	-	29/11/2001
[RD.25]	A.1046(27) Service Requirements for Worldwide Radio Navigation Systems	IMO/A.1046(27)	-	30/11/2011
[RD.26]	MSC.401(95) Performance Standards for Multi-System Shipborne Radionavigation Receivers	IMO/MSC.401(95)	-	8/06/2015
[RD.27]	MSC.1/Circular.1575 - Guidelines for Shipborne Position, Navigation and Timing (PNT) Data Processing – (16 June 2017)	MSC.1/Circular.1575	-	06/2017
[RD.28]	Resolution MSC.112(73) - Adoption of the Revised Performance Standards for Shipborne Global Positioning System (GPS) Receiver Equipment	MSC.112(73)	-	12/2000
[RD.29]	Resolution MSC.53(66) - Performance Standards for Shipborne GLONASS Receiver Equipment - (Adopted on 30 May 1996)	MSC.53(66)	-	05/1996
[RD.30]	Resolution MSC.233(82) Adoption of The Performance Standards for Shipborne Galileo Receiver Equipment - (Adopted On 5 December 2006)	MSC.233(82)	-	12/2006
[RD.31]	RESOLUTION MSC.114(73)) Adoption of The Revised Performance Standards for Shipborne DGPS And DGLONASS Maritime Radio Beacon Receiver Equipment. (Adopted on 1 December 2000	MSC 73/21/Add.3	-	12/2000
[RD.32]	SEASOLAS D030 - Final Report	SEASOLAS-GMV-D030	1.2	05/10/2018
[RD.33]	MaRrinav D1 Maritime Context and Requirement v2.0	-	-	
[RD.34]	Greves, P. D., et al, A portfolio Approach to NLOS and Multipath in Dense Urban Areas *Proceedings of ION GNSS*	-	-	2013
[RD.35]	Satellite derived Time and Position: A study of Critical Dependence, Government Office for Science	-	-	2018
[RD.36]	P.Y Montgomery, T.E. Humphreys, B.M. Ledvina Receiver Autonomous Spoofing Detection: Experimental Results of a Multi-antenna Receiver Defence Against a portable Civil GPS spoofer	-	-	2009
[RD.37]	MarRINav D3b GNSS Integrity: Maritime Integrity at User Level with EGNOS V3 & M-RAIM v2.0	-	2.0	28/02/22
[RD.38]	Hargreaves, Chris. (2019). ENC 2019 - Maritime Receiver Autonomous Integrity Monitoring (M-RAIM).	-	-	2019
[RD.39]	Pervan, B., Pullen, S. and Christine, J. "A Multiple Hypothesis Approach to Satellite Navigation Integrity". Navigation, v.45, no. 1, 1998.	-	-	1998
[RD.40]	IEC, 'Maritime navigation equipment - GNSS, part 1: GPS'.	IEC 61108-1	-	2003
[RD.41]	INSPIRe State of the Art	1.0	-	10/2022

[RD.42]	Blázquez, F, et al, Revision of RAIM implementations for Maritime, *Proceedings of ION GNSS*	-		2020
[RD.43]	IALA World Wide Radio Navigation Plan.	-	1.0	December 2009
[RD.44]	Service development status in the maritime Domain, *EGNOS workshop 2021*, Manuel Lopez Martinez, Silvia Porfili	-	-	December 2021
[RD.45]	IALA guideline G1152 SBAS maritime service	-	1.1	December 2019
[RD.46]	IALA guideline G1129 the retransmission of SBAS corrections using MF-radio beacon and AIS	-	2.0	June 2022
[RD.47]	Minimum Operational Performance Standard for dual-frequency multi-constellation satellite-based augmentation system airborne equipment	ED-259A	Draft	August 2022
[RD.48]	EGNOS Message Server (EMS) User Interface Document	E-RD-SYS-E31-011-ESA	Issue 2 Revision 0	26/11/2004 .

3 STATE OF THE ART REVIEW

3.1 Introduction

This section provides a review and consolidation of the current situation regarding maritime integrity, and previous activities that have investigated approaches for integrity in the maritime domain. The review will reflect on user-level integrity for single frequency GPS, considering the two maritime scenarios: is a maritime-specific implementation of the aviation ARAIM concept and performs a multiple-hypothesis solution-separation process, then computes a protection level and iteratively optimises this PL through re-allocation of integrity risk, and the second : which is a chi-squared fault-detection process with simple geometric screening rules to ensure safety , (Maritime General RAIM (MGRAIM)).

It starts with a review of the situation in aviation, then looks at maritime requirements for integrity, and finally highlights current issues with integrity in maritime and differences from aviation.

3.2 GNSS Integrity in Aviation

3.2.1 Introduction to Integrity

Aviation has traditionally been seen as the driver for GNSS integrity concepts, and has well defined requirements, concepts, and standards. As such, it is sometimes seen as a model for maritime to follow. Therefore, in this section we first discuss navigation performance and integrity with regards to aviation.

GNSS performance requirements can be expressed in terms of accuracy, integrity, availability and continuity (see civil aviation standards [RD.1]):

- **Accuracy:** this parameter evaluates the difference between the real position of the user and the position provided by the navigation aid system. Accuracy requirements are given as a statistical figure of the position error (typically, the maximum allowable 95% percentile)
- **Integrity:** it measures the confidence in the correctness of the information supplied by the system, including the ability to provide timely alerts to the user when the requirements are not ensured to be met.
- **Continuity:** is the probability that the specified system performance will not be interrupted for the duration of a phase of operation, assuming that the system was available at the beginning of that phase of operation and that was predicted to run all over the operation.
- **Availability**: is the percentage of time that the GNSS system is available to provide accurate positioning and navigation services. Availability indicates the system's ability to provide usable service within the specified coverage area. Signal availability is the percentage of time that navigation signals transmitted from external sources are available for use.

These performance-related terms are closely linked to each other and form together a set of performance requirements that need to be satisfied allowing for a successful accomplishment of a user's operation. The accuracy requirement (statistical figure over the position error) is crucial for any GNSS application, and it is a prerequisite in safety-critical applications. Then, the system is declared continuous if integrity is ensured at the beginning and throughout the period of an operation. Availability is given if integrity, continuity, and accuracy are available.

It is worth mentioning that accuracy and integrity concepts could be somehow confused. For this reason, the differences among both concepts are presented so they can be understood without a deep background in GNSS concepts.

The first step is to understand the concept of accuracy, so it is not confused with precision:

Accuracy indicates how close is my estimated position from the real position

Precision indicates how close are the estimated positions to each other

On the other hand, integrity is conceptually explained below:

Integrity aims to indicate whether I can trust or not my GNSS data.

Figure 3-1 presents graphically the differences among accuracy and precision concepts, whereas Figure 3-2 shows the differences among accuracy and integrity concepts in a visual way:

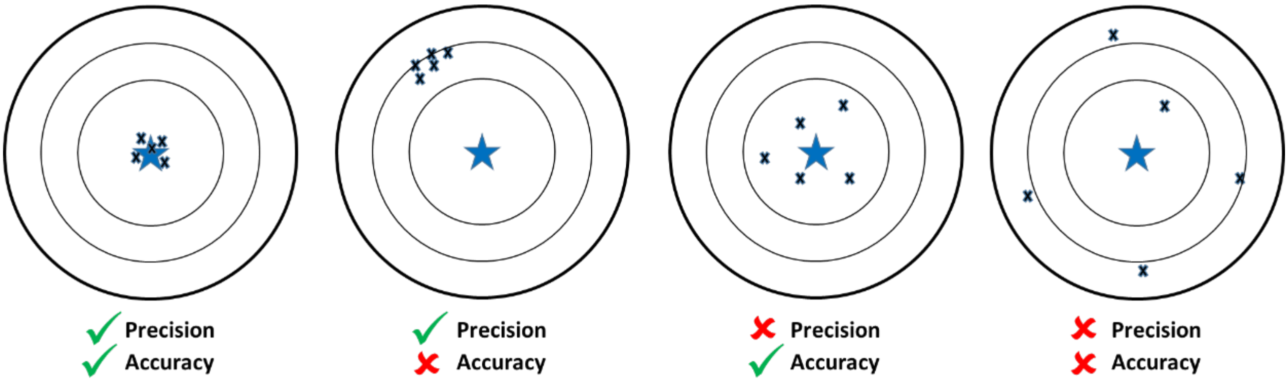


Figure 3-1: Accuracy vs Precision

Figure 3-2: Integrity vs Accuracy [RD.3]. Figure @gmv

Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation. In aviation, GNSS integrity is measured in the following terms:

- Alert limit (AL): is the error tolerance not to be exceeded without issuing an alert. Both horizontal and vertical alarm limits[1] shall be defined.
- Time to Alert (TTA): this is the maximum allowable time elapsed from the onset of the navigation system being out of tolerance (e.g., position error exceeding the alert limit) until the equipment annunciates the alert.
- Out of tolerance: this is defined as a horizontal error exceeding the HPL or a vertical error exceeding the VPL [RD.5].
  - The horizontal error is referred to as HPE (Horizontal Position Error),
  - The vertical error is referred to as VPE (Vertical Position Error).

[1] For a formal definition of the Horizontal and Vertical Alarm Limits, please refer to the aforementioned civil aviation standards.

An out of tolerance event occurs when one of both following events occurs:

- HPE > HPL or,
- VPE > VPL (in absolute value)

This is discussed further in the next section.

- Integrity risk (IR): the probability that, at any moment, the position error exceeds the out of tolerance condition without issuing an alert.
- Protection levels: The following protection levels are defined according to RTCA SBAS MOPS [RD.4]:
  - The Horizontal Protection Level (HPL) is the radius of a circle in the horizontal plan, with its centre being at true position, which describes the region which is assured to contain the indicated horizontal position. It is the horizontal region for which the missed alert requirement can be met. It is based upon the error estimates provided by SBAS. HPL provides a bound on the horizontal position error with a probability derived from the integrity requirement
  - The Vertical Protection Level (VPL) is the half length of a segment on the vertical axis with its centre being at the true position, which describes the region which is assured to contain the indicated vertical position. It is the vertical region for which the missed alert requirement can be met. It is based upon the error estimates provided by SBAS. the VPL provides a bound on the Vertical Position Error.

  The Horizontal Protection Level (HPL) provides a bound on the horizontal position error with a probability derived from the integrity requirement. Similarly, the Vertical Protection Level (VPL) provides a bound on the Vertical Position Error.

3.2.2 *Integrity monitoring*

What is important to the user is that the GNSS position error is not larger than a certain value, where the position error is defined as the difference between the estimated position and the true position. However, the position error (xPE, being x equal to H in horizontal, V in vertical domain) is unknown because the true position is also unknown: the only thing the user has that can help is a statistical knowledge of the likely position error. For this reason, the accuracy requirement is defined for each estimated position such that the probability of the estimated position being inside the accuracy bound must be at least 0.95 (assuming the position error is a normal distribution with standard deviation equal to σ, the 95% confidence interval is equivalent to 2σ).

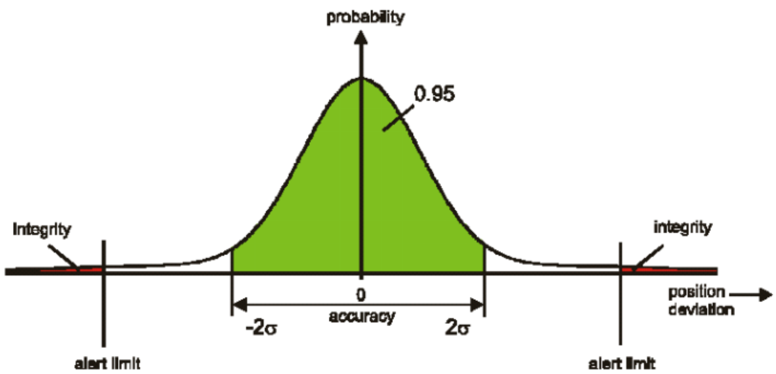


Figure 3-3: Integrity risk graphic definition [RD.6]

The ideal case would be to compare the alert limit (xAL) with the position error. However, during normal operations is not possible to know the position error of the user, so integrity monitoring techniques currently employed in civil aviation check the compliance with the integrity requirements calculating statistical confidence bounds of the position error: the so-called **protection levels** (xPL). In this way, the protection levels can be seen as conservative bounds of the positioning error so that the probability of the position error exceeding said number is smaller than or equal to the integrity risk (red area in Figure 3-3).

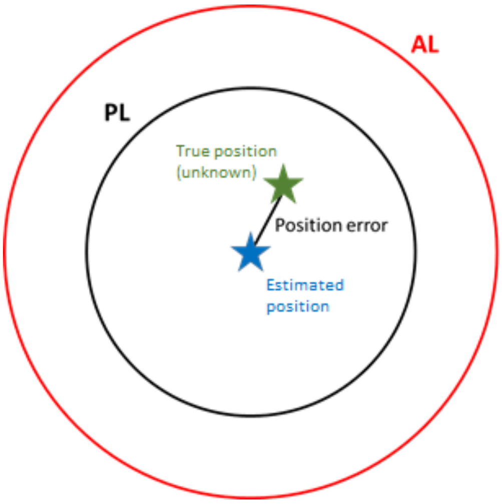


Figure 3-4 Protection level concept

Figure 3-5 shows the definition of protection level from an aviation operational perspective:

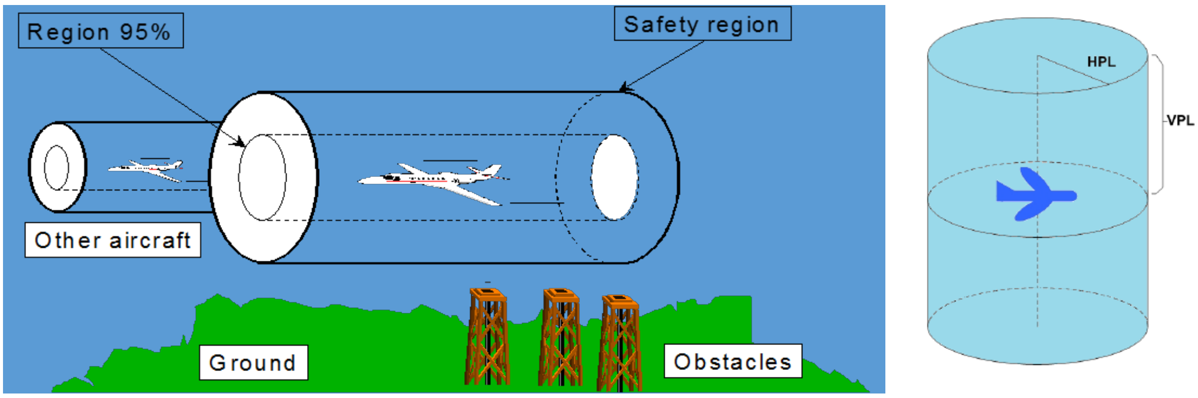


Figure 3-5: Definition of Protection Level (based on [RD.4])

The ideal case would be to compare the xAL (x stands either H or V) with the xPE. Obviously, we don't know the xPE. Therefore, the mechanism is only able to compare the xPL (as a conservative estimate of the xPE) with the xAL.

This mechanism would be perfect if and only if the xPL was the perfect estimate of the real error (the xPE). Unfortunately, this is not the case. The effects of a gap between the xPL and the xPE could be as followed:

- If the xPL is too much higher than the xPE, this could induce an availability problem for the system.
- If the xPL is lower than the xPE, this could induce an integrity problem for the system. The event for which xPL < xPE is sometimes called misleading information (MI).

Next figure shows the different possibilities that can occur in terms of availability and integrity particularized to Alarm Limits (xAL), Protection Levels (xPL) and Position Errors (xPE) concepts.

- If the xPE is lower than the xPL and the xPL is lower than the Alarm Limit (xAL) the system is considered available and with integrity
- If the xPE is lower than the xPL, it means that the system provides integrity, if the Protection Level (xPL) is greater than the Alert Limit (xAL) the system will not be available. In this case, integrity is provided but the system is not available. This is a typical situation of False Alarm.
- If xPL is lower than the xPE, this could induce an integrity problem for the system.
    - If the xAL is greater than the xPL the system will be available, and therefore there will be an integrity problem. This is a typical situation of misleading information (MI) for aviation applications.
    - If the xAL is greater than the xPL and the xPE is both greater than the xAL and the xPL the system will be available, and therefore there will be an integrity problem. This is a typical situation of hazardously misleading information (HMI) both for aviation and railway applications.
    - If the xAL is lower than the xPL the system will not be available, and therefore the *integrity is preserved*. In this case, the system will be not available, but it will have integrity

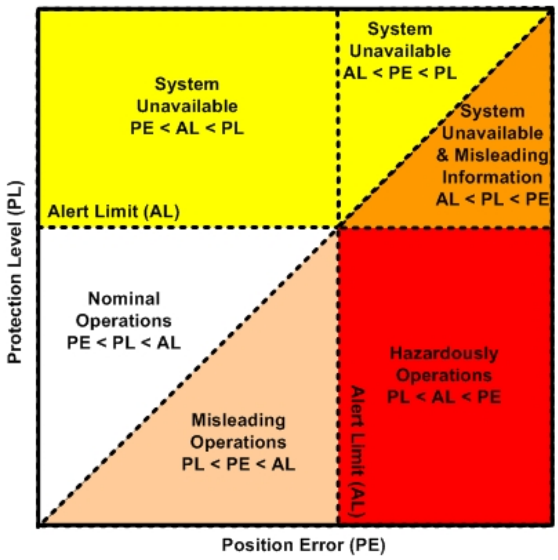


Figure 3-6: Stanford diagram [RD.7]

There is a trade-off to define between the risk of integrity failure and the availability of the system. As a matter of completeness, apart from the differences between accuracy and integrity concepts from Figure 3-6 at a conceptual level there are also other differences as indicated below. This content has been extracted from [RD.7]:

- *From a mathematical point of view, the main difference between them is the point of the tail of the statistical distribution of errors at which to place the cut-off. For instance, civil aviation requirements tend to measure accuracy at the 95% percentile (e.g., "95% of the errors shall be below a predetermine threshold limit."), whereas integrity requirements refer to percentiles that range between 99.999% and 99.9999999% (depending on the topic under consideration). The intention behind this is to keep the probability of hazardous situations (that would possibly put at risk human lives) extremely low. Please refer to* Figure 3-3 *for a graphic representation of this aspect.*
- *Another key difference is in the alarms; integrity requirements involve alarms being raised when system's performance is bad enough to become risky, while accuracy requirements do not.*

- *From a system performance perspective, accuracy is understood as a global system characteristic, whereas integrity is rather intended as real time decision criterion for using or not using the system. For this reason, it has been a common practice to associate integrity with a mechanism or set of mechanisms (barriers) that is part of the integrity assurance chain but at the same time is completely independent of the other parts of the system for which integrity is to be assured.*

3.2.3 GNSS Integrity Concept

In general, there are two different integrity concept levels that are applicable for aviation: system level integrity, where some fixed infrastructure monitors the GNSS satellites to identify potential faults and disseminates alerts to user receivers, and user level integrity, where the user receiver itself checks the GNSS signals to detect faults taking into account the surrounding environment.

3.2.3.1 System Level Integrity

Two types of augmentation systems devoted to providing integrity for aviation can be found:

- **Satellite Based Augmentation Systems (SBAS):** it is a wide coverage augmentation system in which the user receives augmentation information from a satellite-based transmitter. It is composed of a network of monitoring stations which collect GNSS data from constellations and then a processing facility analyses it to generate the corrections to the Signal in Space (SIS) data. This information is sent by a set of uplink stations to geostationary satellites which broadcast the corrections to the user.

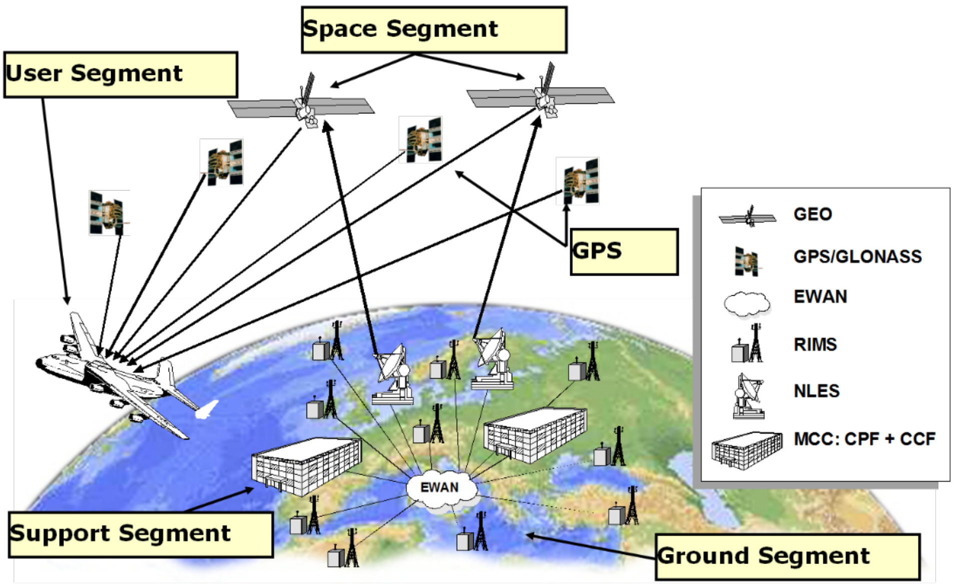


Figure 3-7 SBAS System Architecture [RD.8]

- **Ground Based Augmentation Systems (GBAS):** in this case the user receives augmentation information directly from a ground-based transmitter. The ground system includes two or more GNSS receivers which collect the satellites data and sends it to a ground facility that computes the corrections. The information is broadcasted to the user through a VHF transmitter. Please note that this augmentation system is devoted to local areas.

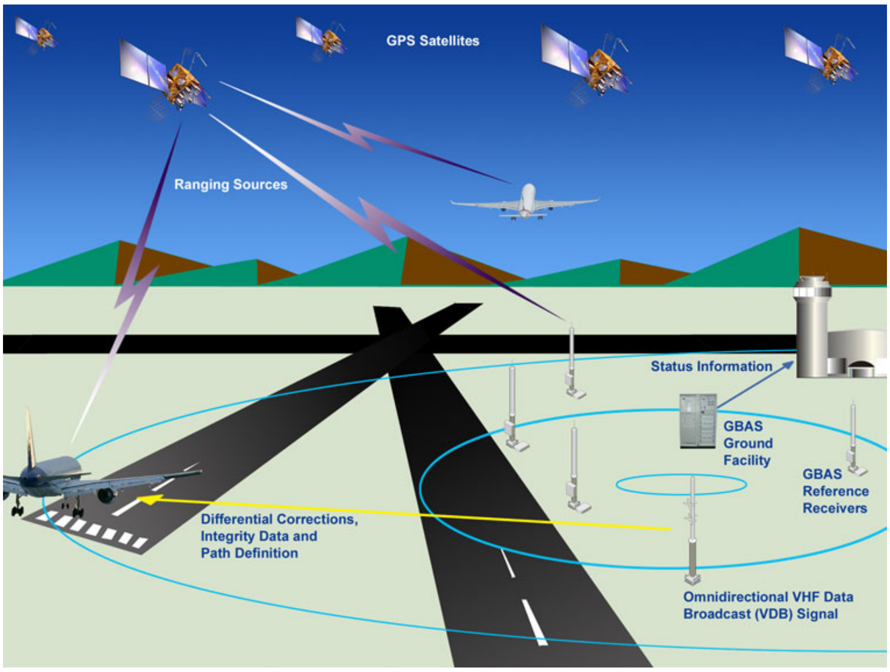


Figure 3-8 GBAS Architecture [RD.9]

In both SBAS and GBAS systems, the user is provided with corrections to improve the accuracy of the system, which can help the solution meet more stringent performance requirements for different phases of flight.

Also, in SBAS and GBAS systems, the ground segment is responsible for processing the GNSS SIS data and detecting potential satellite measurement failures, which are disseminated to the user within a specified time to alarm. Hence, by rejecting those satellites for which faults have been detected, the user can be assured that navigation is performed with fault-free data.

The main difference between SBAS and GBAS systems is that GBAS is a local augmentation system, serving a particular airport for example, whereas SBAS is a wide area system providing a service over an entire region (e.g., EGNOS for Europe, WAAS for the US). For INSPIRe, the potential use of EGNOS to provide system level integrity over the UK is a consideration and so SBAS integrity is discussed in more detail here.

3.2.3.1.1 SBAS Performance Characteristics

The classical GNSS performance parameters have been defined by and tailored to the aviation domain. The aviation industry's ICAO has published SARPs that provide high level guidance for the design and certification of SBAS systems.. This section discusses the classical GNSS position domain concepts of accuracy, availability, integrity and continuity, for each type of operation related to the performance categories [RD.1][RD.5]. The typical operations for aircrafts are:

- En-route
- En-route, terminal
- Initial approach, intermediate approach, non-precise approach (NPA), departure
- Approach operations with vertical guidance (APV-I)
- Approach operations with vertical guidance (APV-II)
- Category I precision approach (CAT-I)

The performance requirements for each type of operation are detailed in Table 3-1extracted from [RD.5].

Table 3-1. Aviation Performance Requirement [RD.5]

Typical Operation	Horizontal Accuracy (95%)	Vertical Accuracy (95%)	Integrity	Time-To-Alert (TTA)	Horizontal alert limit	Vertical alert limit	Continuity	Availability
En-route	3.7 km (2.0 NM)	N/A	$1 - 1 \times 10^{-7}$/h	5 min	7.4 km (4 NM)[2] 3.7 km (2 NM)[3]	N/A	$1–1 \times 10^{-4}$/h to $1–1 \times 10^{-8}$/h	0.99 to 0.99999
En-route Terminal	0.74 km (0.4 NM)	N/A	$1 - 1 \times 10^{-7}$/h	15 s	1.85 km (1 NM)	N/A	$1–1 \times 10^{-4}$/h to $1–1 \times 10^{-8}$/h	0.99 to 0.99999
NPA	220 m (720 ft)	N/A	$1 – 1 \times 10^{-7}$/h	10 s	556 m (0.3 NM)	N/A	$1–1 \times 10^{-4}$/h to $1–1 \times 10^{-8}$/h	0.99 to 0.99999
APV-I	16 m (52 ft)	20 m (66 ft)	$1 - 2 \times 10^{-7}$ per approach	10 s	40 m (130 ft)	50 m (164 ft)	$1–8 \times 10^{-6}$ in any 15 s	0.99 to 0.99999
APV-II	16 m (52 ft)	8 m (26 ft)	$1 - 2 \times 10^{-7}$ per approach	6 s	40 m (130 ft)	20 m (66 ft)	$1–8 \times 10^{-6}$ in any 15 s	0.99 to 0.99999
CAT-I	16 m (52 ft)	6.0 m to 4.0 m (20 ft to 13 ft)	$1 - 2 \times 10^{-7}$ per approach	6 s	40 m (130 ft)	15 to 10 m (50 to 33 ft)	$1–8 \times 10^{-6}$ in any 15 s	0.99 to 0.99999

As part of the EGNOS SoL service provision, Localizer Performance with Vertical guidance-200 (LPV-200) service level is currently available for operational use.

LPV-200 horizontal and vertical accuracy performances are detailed in Table 3-2. The EGNOS system is therefore compliant with the ICAO SoL service performance requirements specified in [RD.5] for Category I precision approach with a Horizontal Alert Limit of 40m and Vertical Alert Limit of 35m inside the availability service area defined in Section 6.3.3.4 of [RD.5].

Table 3-2 EGNOS SoL Service Performance values, (extracted from [RD.5])

[2] En-route (oceanic/continental low density)

[3] En-route (continental)

		Accuracy		Integrity		Continuity	Availability
		Horizontal Accuracy 95%	Vertical Accuracy 95%	Integrity	Time-To-Alert (TTA)		
Performance	APV-I & LPV-200	3 m	4 m	$1 - 2\text{x}10^{-7}$ / approach	Less than 6 seconds	<1 – $1\text{x}10^{-4}$ per 15 seconds in the core of ECAC 1 – $5\text{x}10^{-4}$ per 15seconds in most of ECAC landmasses	0.99 in most of ECAC landmasses

EGNOS APV-I and LPV200 availability are defined as the percentage of epochs which the Protection Level are below Alert Limits for this APV-I service (HPL<40m and VPL<50m) and (HPL<40m and VPL<35m) respectively over the total period. This value corresponds to the performance obtained under fault-free conditions using all satellites in view

Figure 3-9, provides the minimum availability performance that can be expected from EGNOS for LPV-200. The different shaded areas represent the different availability requirements, the area in dark red represents the area where the 99.9%, orange - 98%, green - 90% and dark blue - 70%. Service is not provided outside the coloured areas due to the non-compliance in those regions with the accuracy requirements imposed to LPV-200 service level

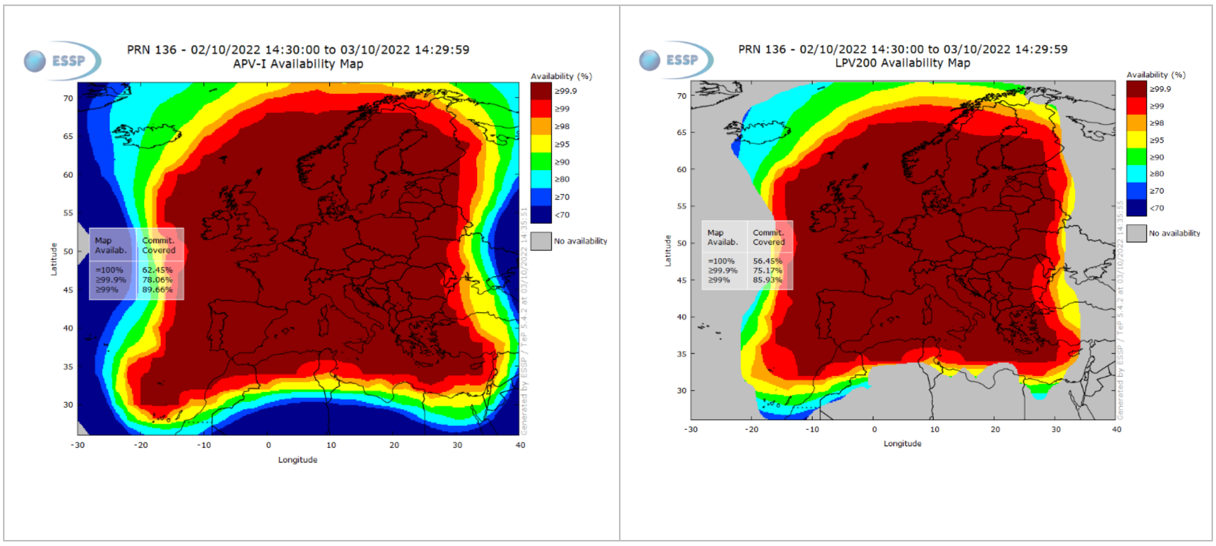


Figure 3-9 EGNOS APV-I and LPV-200 Availability Map [RD.10]

A sense of the likelihood of the service being unavailable for longer than one second at a time can be obtained from the service Continuity parameter.

Continuity of service of a system is defined in [RD.5] as the capability of the system to perform its function without unscheduled interruptions during the intended operation. It relates to the capability of the navigation system to provide a navigation output with the specified accuracy and integrity during the approach, assuming that it was available at the start of the operation.

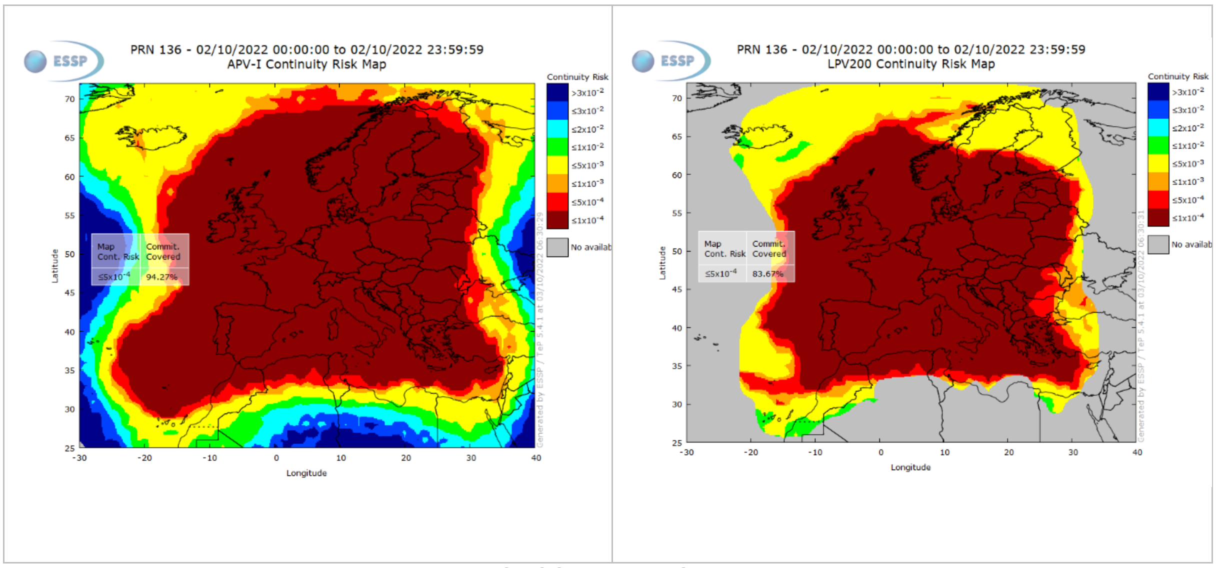


Figure 3-10 EGNOS LPV-200 Continuity [RD.10]

Figure 3-10, provides the minimum continuity performance that can be expected from EGNOS for AP-I and LPV-200. These values correspond to the expected minimum performance measured by a fault-free receiver using all satellites in view, when averaging over a period of one month, using all the operational EGNOS GEOs [RD.5]. A single continuity event occurs if the system is available at the start of the operation and in at least one of the following 15 seconds the system becomes not available. Consequently, grey area shown in maps also includes the area in which LPV200 accuracy requirements are not fulfilled.

3.2.3.1.2 Computing the Protection levels

Essentially, SBAS systems consist of a network of ground reference stations at known locations that track the GPS satellites and provide the measurements to a central processing facility. This uses the measurements from the ground reference stations to compute corrections to certain errors:

- Corrections to the orbit and clock models in the GPS navigation message
- Corrections for single frequency users to apply in order to better remove ionospheric effects

Quality indicators for the corrections (UDRE for orbit/clock and GIVE for ionospheric delay values) are also computed.

All the information is formatted into standard messages, and these are uploaded to Geostationary satellites for broadcast on L-band signals to users.

The purpose of the SBAS protection level is to “protect the user against misleading information (MI) due to data corrupted by the noise induced by the measurement and algorithmic process when the system is in a nominal state (no GNSS satellite failure, no ground segment/user equipment failure)” [RD.1]. The SBAS Protection level equations are computed using the following equations

SBAS protection level equations are defined in ICAO SARPS [RD.1] and RTCA MOPS [RD.4] as:

$$HPL = K_H \times d_{major}$$

$$VPL = K_V \times d_U$$

where,

$$\boldsymbol{d_{major}} = \sqrt{\frac{\boldsymbol{d^2_{east}} + \boldsymbol{d^2_{north}}}{\mathbf{2}} + \sqrt{\left(\frac{\boldsymbol{d^2_{east}} - \boldsymbol{d^2_{north}}}{\mathbf{2}}\right) + \boldsymbol{d^2_{EN}}}}$$

$d^2_{east} = \sum_{i=1}^{N} s^2_{east,i}\sigma^2_i$ which is the variance of model distribution that over bounds the true error distribution in the East axis;

$d^2_{north} = \sum_{i=1}^{N} s^2_{north,i}\sigma^2_i$ is the variance of model distribution that over bounds the true error distribution in the North axis;

$d^2_{EN} = \sum_{i=1}^{N} s_{U,i}\sigma^2_i$ is the variance of model distribution that overabounds the true error distribution on the vertical axis.

$d^2_{U} = \sum_{i=1}^{N} s_{U,i}s_{north,i}\sigma^2_i$ is the covariance of model distribution in the East and North axes.

$s_{east,i}$ = the partial derivative of position error in the East direction with respect to the pseudorange error on the i^th^ satellite (see definition of matrix *S* below)

$s_{north,i}$ = the partial derivative of position error in the North direction with respect to the pseudorange error on the i^th^ satellite (see definition of matrix *S* below)

$s_{U,i}$ is the partial derivative of position error in the vertical direction with respect to the pseudorange error on the i^th^ satellite.

The matrix S is defined as :

$$S = \begin{bmatrix} s_{east,1} & s_{east,2} & \cdots & s_{east,N} \\ s_{north,1} & s_{north,2} & \cdots & s_{north,N} \\ s_{U,1} & s_{U,2} & \cdots & s_{U,N} \\ s_{t,1} & s_{t,2} & \cdots & s_{t,N} \end{bmatrix} = (G^T \cdot W \cdot G)^{-1} \cdot G^T \cdot W$$

where,

G is the geometry/linearization/design matrix

W is the weighting matrix

t_{G1} represents the receiver time offset with respect to constellation 1

t_{G2} represents the receiver time offset with respect to constellation 2

K Factor

K_H and K_V are the horizontal and vertical K-factors respectively based on the probability of missed detection requirement.

The K factor is selected based on the assumed statistical distribution of the position errors and the probability of missed detection requirement. [RD.4] indicates the K Factor values as follows:

$K_{H,NPA} = 6.18$ for enroute through LNAV

$K_{H,PA} = 6.0$ for LNAV/VNAV, LP, LPV

$K_V = 5.33$

Error modelling

In determining an SBAS protection level, pseudorange errors are modelled as follows

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

where

$\sigma_{i,flt}^2$ – Variance of fast and long-term Correction,

$\sigma_{i,UIRE}^2$ – Variance of Ionosphere Delay

σ_{air} – Variance of Receiver errors

$$\boldsymbol{\sigma_{i,air}} = (\boldsymbol{\sigma^2_{noise,GPS}}[\boldsymbol{i}] + \boldsymbol{\sigma^2_{multipath}}[\boldsymbol{i}] + \boldsymbol{\sigma^2_{divg}}[\boldsymbol{i}])^{\boldsymbol{1/2}}$$

σ_{noise}^2 is defined as the standard deviation of a normal distribution that bounds the errors in the tails of the distribution associated with the GNSS receiver, including receiver noise, thermal noise, interference, inter-channel biases, extrapolation, time since smoothing filter initialisation, and processing errors. It is also stated that σ_{noise}^2 should change to reflect current signal conditions, giving the example of it being necessary to capture the degradation to system accuracy due to interference within protection level computations.

σ_{divg}^2 is defined as being greater than or equal to the differentially corrected pseudorange error induced by the steady-state effects of the airborne smoothing filter relative to the steady-state response of the filter defined in the MOPS, given an ionospheric divergence that is defined to have a constant rate of 0.018 m/s. It is stated that if the airborne smoothing filter converges to a different steady-state bias than the standard filter, a steady-state error will remain which must be accounted for in σ_{divg}^2.

The sum of the noise and divergence terms is specified as a constant in legacy MOPS (DO-229E), depending on the 'Airborne Accuracy Designator' and the power conditions. The worst case is set as given as

$$(\sigma_{noise,GPS}^2[i] + \sigma_{divg}^2[i])^{1/2} = 0.36\ metres$$

Multipath is aviation is defined as an elevation dependent multipath model that reflects the aviation environment, where there are very few environmental features which may cause multipath, (typically limited to the aircraft body itself and airport infrastructure when on the ground or landing). It is defined as:

$$\sigma_{multipath}[i] = 0.13 + 0.53e^{(-\theta[i]/10deg)}\text{, in metres}$$

It is noted in the RTCA MOPS [RD.4] that the multipath error model was developed and validated using data from flight tests conducted on a variety of fixed wing aircraft, and it is designed to bound the tails of the error distribution for 100-second carrier smoothed pseudoranges from a complaint GPS antenna in that environment. This means the model is well validated for aviation but is not directly transferable to other domains.

3.2.3.2 USER Level Integrity Concept

The above-mentioned augmentation system provides integrity at the system level using differential corrections and integrity related information. These methods do not consider the local environment of the user, or the operation of their receiver, hence user-level integrity can only be achieved by the receiver itself. This section describes some of the available integrity concepts for GNSS technologies, considering different kind of processing

These autonomous integrity techniques apply a different strategy for detecting faults to the system integrity concept. Users held integrity assurance responsibility, detecting satellite faults based on the use of redundant measurements over a user algorithm and to exclude the failed measurements from the position calculation assessment. On the other hand, system level integrity concepts rely on monitoring systems that analyse the confidence of the SiS information and provide alarms to the user. In the later concept the user just have to decode and interpretate received messages.

One of the most common autonomous integrity techniques is RAIM, which provides an indication if the position calculated is likely to be outside of the requirements of performance standards.

Standards such as RTCA-DO-316 [RD.14] define minimum performance, functions and features for GPS sensors that implement FDE mechanisms. SBAS MOPS [RD.4] further refers to RAIM as a reversionary mode FDE when SBAS monitoring is not available. It is worth mentioning that these standards do not establish any particular RAIM algorithm to be implemented but requirements that they must fulfil.

There are many algorithms in the literature, in general the techniques are based on the use of redundant information to detect the presence of a faulty satellite range and likely positioning failure. Upon detection, proper fault exclusion determines and excludes the source of the failure to allow GNSS navigation to continue without interruption. A modernised version of RAIM has been defined, called Advanced RAIM (ARAIM) [RD.15]. The following sections explore the most relevant RAIM concepts.

3.2.3.2.1 Classical RAIM

The term Classical RAIM refers to fully autonomous algorithms which can implement only one, a combination, or all of the following capabilities: Fault detection, Fault exclusion and Protection Level computation. The classical RAIM algorithm is a snapshot approach (working on a single epoch of data at a time) to compare the pseudorange measurements among themselves to ensure that they are all consistent. RAIM algorithms make use of measurements redundancy to check the relative consistency among them (by means of the residuals) and in the case of detection, the most likely “failed” satellite is determined. A key assumption usually made in RAIM algorithms for civil aviation is that only one satellite may be faulty, i.e., the probability of multiple satellite failures is negligible. Another key issue related to RAIM algorithms is that one of their goals is to find measurement errors that diverge from non-nominal situations.

Classic RAIM techniques comprise Fault Detection (FD), Fault Exclusion (FE) and Protection Level (PL) functions. FD and FE functions (usually grouped in the acronym FDE) make use of pseudorange residuals of the all-in-view least-squares position solution. The very existence of pseudorange residuals is a consequence of measurement redundancy on which Classic RAIM (as all other RAIM methods) rely. Conditioned to FD success, protection levels are computed based on satellite geometry and a priori information on the statistical distribution of measurement errors, and the likelihood of *feared events*, or faults.

The FE function is called only rarely when the FD function raises a detection flag. On the other hand, the functions FD and PL are called routinely once per epoch in sequence (FD first, then PL), with the following exceptions:

- If, at a given epoch, the least squares position cannot be computed (e.g., due to not enough measurements or bad geometry) or if it leaves no residuals (i.e., no measurement redundancy), then none of the classic RAIM functions are called
- If the FD function raises a detection flag and there are at least two redundant measurements, the PL function is left on hold. The FE function is called instead, which excludes one or more satellites. Then the PL function is called. Some implementations do not call the PL function directly after FE but make a recursive call to the full RAIM function with the new set of measurements, which excludes those rejected by the FE function. In the recursive approach, each call to the FE function excludes only one satellite. At each new recursion step the least squares solution must be called with the new set of measurements, generating a new state estimate and a new set of residuals prior to entering the RAIM function. The recursive loop is broken when the FD test passes (in which case the PL function is finally called) or when there are too few redundant measurements left to continue (in which case the PL function is not called, and integrity is declared unavailable).

In terms of how the RAIM algorithm operates, the following example is provided for a simple weighted RAIM algorithm defined in [RD.22].

- Firstly, there must be more measurements available than unknowns in order to check the consistency of the measurements. In a GPS only case this means there must be at least 5 satellites used (if estimating 3D position and receiver clock offset).
- Then a recursive snapshot weighted least squares solution is computed

  $$x = (G^T W G)^{-1} G^T W y, \text{ or}$$

  $$x = K.y$$

  where

  G is the geometry/linearization/design matrix

  W is weight matrix

  y is the vector containing observed minus computed ranges
- From this the confidence for the vertical and horizontal accuracy values are computed:

  $$\sigma_v = \sqrt{[(G^T W G)^{-1}]_{3,3}}$$

  $$HRMS = \sqrt{[(G^T W G)^{-1}]_{1,1} + [(G^T W G)^{-1}]_{2,2}}$$

- Next, a check is done to detemne if a fault is detected by forming a test statistic, which measures the ‘goodness of fit’ of the measurement residuals (i.e. their consistency), and comparison this against a threshold. A common test statistic is the Weighted Sum of the Squared Errors:

  $$WSSE = y^T W(I - P)y$$

  where

  $$P = GK = G(G^T WG)^{-1} G^T W$$

- The square root of WSSE, is checked against a threshold T to identify faults, where the threshold is chosen analytically based on the number of satellites in view and required probability of false alarm, if the test statistic follows a chi-square distribution in the fault-free case.
- If a fault is detected then an identification and exclusion process may take place, by removing each satellite one at a time and rechecking the test statistic: in this case the single set that does not contain the faulty satellite may have test statistic below the threshold
- If after fault detection (and exclusion) a solution is available for which no fault is detected, the final step is to compute a protection level. This maps the test statistic (or for prediction purposes the threshold) through to the position domain to provide a guarantee of the maximum position error that could exist in the solution without having been detected.
- The test statistic (or threshold) is mapped to the position domain through the satellite slope. In the vertical domain, for example, the slope is defined as:

  $$Vslope_i = \frac{|K_{3,1}|\sigma_i}{\sqrt{1 - P_{i,i}}}$$

- The protection level is then computed as the combination of the impact through slope and the nominal accuracy, i.e.

  $$VPL_{FD} = max[Vslope].T + k(P_{md}).\sigma_v$$

  $$HPL_{FD} = max[Hslope].T + k(P_{md}).HRMS$$

[RD.22] illustrates this graphically as shown below.

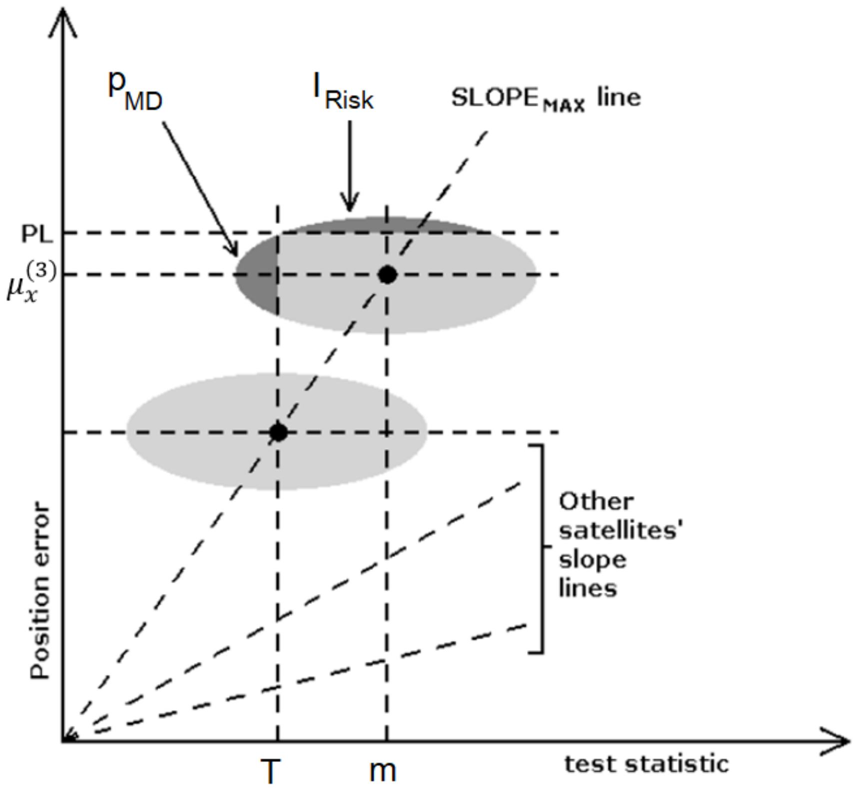


Figure 3-11: Illustration of a Classical RAIM scheme and Protection Level Computation [RD.22]

$$VPL_{FD} = max[Vslope].m + k(I_{risk}).\sigma_v$$

$$HPL_{FD} = max[Hslope].m + k(I_{risk}).HRMS$$

- The protection level is then checked against the defined alert limit for the operation to see if the solution is available. If the protection level is greater than the alert limit then it cannot be guaranteed that there are not undetected errors in the solution that would make the solution unsuitable for navigation and so the solution is said to be unavailable.

Classic RAIM techniques have the advantage over augmentation system of not needing ground infrastructure since these techniques are autonomous at receiver level. Classic RAIM, being an integrity technique at user level, has also the advantage with respect to system integrity to be able to handle both system events and local events. Another advantage of classic RAIM is that the detection of a failure is instantaneous while for SBAS/GBAS there is a maximum Time-To-Alert (TTA) of 6 seconds.

Nevertheless, RAIM has several deficiencies compared to SBAS/GBAS systems. Firstly, without receiving any correction information, the accuracy of the solution is degraded compared to SBAS or GBAS systems. This is particularly the case for single frequency solutions where the ionospheric errors dominate. This also affects integrity where the confidence levels must be very stringent, since the conservative assumptions that are necessary for the error models tend to degrade its performances significantly.

In the same way as for the EGNOS performance (see Figure 3-9), RAIM availability can be assessed by computing the protection levels for each epoch within a selected time period at a grid of points and comparing the values with the defined alert limit for the operation. [RD.23] assessed the RAIM availability of the current GPS constellation over the entire globe at spatial and temporal sampling intervals of five degrees and five minutes respectively. The assessments were done for the non-precision approach (NPA) and precision approach (APV I and APV II) phases of flight, considering the GNSS Aviation Operational Performance Requirements the integrity requirements. Figure 3-11 to 3-13 extracted from [RD.23] displays the results of the assessment.

Figure 3-12 illustrates the RAIM availability for NPA using a horizontal alarm limit (HAL) of 556 m, the graph shows that the availability of RAIM for NPA is less than 98% in the mid latitude regions. Figure 3-13 and Figure 3-14 displays the horizontal RAIM availability for precision approaches, APVI and APVII respectively. The APV I plot shows similar results to NPA mainly because the requirements are largely the same. The APV II 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

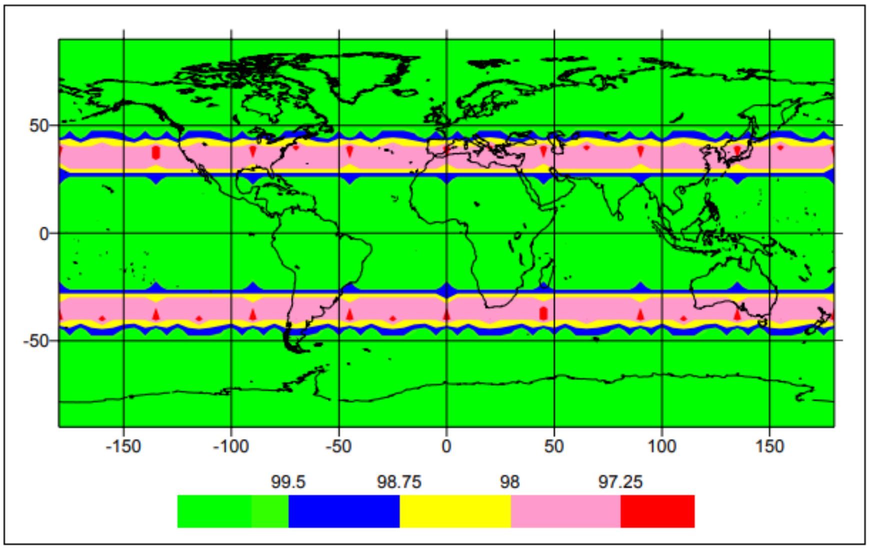


Figure 3-12 NPA GPS Horizontal RAIM Availability [RD.23]

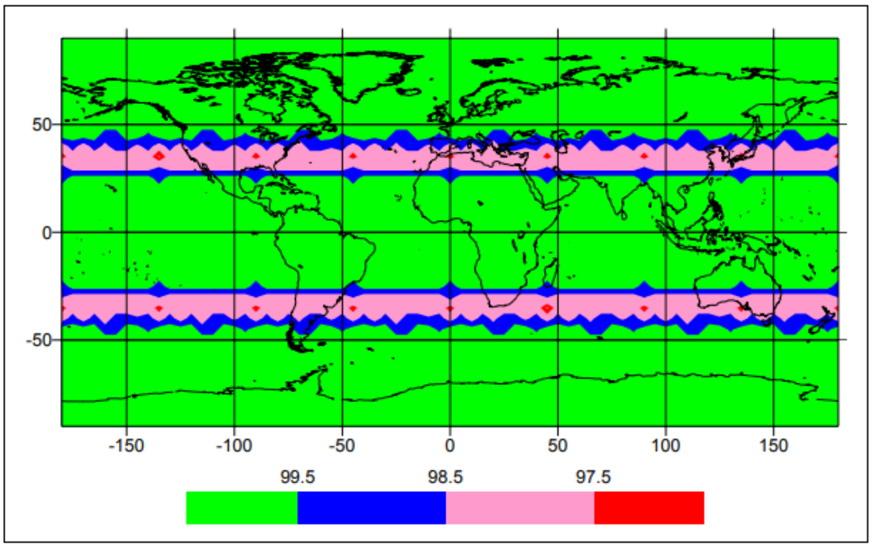


Figure 3-13 APV I GPS Horizontal RAIM Availability[RD.23]

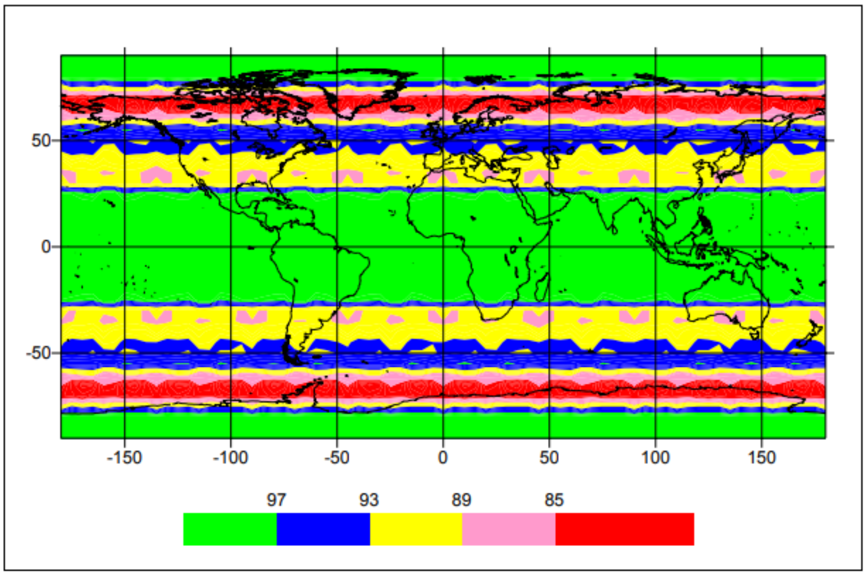


Figure 3-14 APV II GPS Horizontal RAIM Availability [RD.23]

Compared to the EGNOS performance it can be seen that the RAIM service is global (i.e., values are obtained at all locations) but the availability figures are lower than can be achieved with EGNOS.

Potentially the availability of classic RAIM can be improved using dual-frequency measurements to remove ionospheric errors (which then has less uncertainty than use of the broadcast error model) and use of multi-constellation measurements (to improve geometry).

However, classic RAIM is insufficient in a multi-constellation context due to the assumption of single failure, which may not hold as more satellites and constellations are used. This means that classic RAIM cannot be accommodated as it currently stands in the DFMC trend being adopted in many GNSS sectors and applications, which is evolving towards the use of multiple constellations and frequencies, and therefore the availability performances of RAIM are penalized by the fact of being able to use only a single constellation. Finally, RAIM assumes that measurement errors not excluded follows a biased Gaussian distribution, which is not always true for all circumstances.

In summary some identified advantages of RAIM for with respect to system integrity (SBAS and GBAS) are:

- RAIM algorithm does not need any ground infrastructure and any information dissemination since the technique is purely at receiver level.
- RAIM provides a global service, as opposed to GBAS or SBAS which provides a local/regional service respectively since they need dissemination of key safety information.
- RAIM provides a certain level of protection against local effects, which is especially important in the typical environments of non-aviation applications, as far as single-failure and error characterisation assumptions are deemed acceptable.
- In addition, RAIM detection of a failure is instantaneously while for SBAS/GBAS there is a Time-To-Alert (TTA) of 6 seconds.

On the other hand, some identified limitations of RAIM are:

- One of these assumptions is that measurement errors not excluded follows a biased Gaussian distribution, which is not always true for all circumstances. This may cause that the integrity of the RAIM algorithm may be compromised.
- Due to the assumption of single failure RAIM cannot be accommodate in the DFMC trend being adopted in many GNSS sectors and applications which is evolving towards the use of multiple constellations and frequencies and therefore, the availability performances of RAIM are penalized by the fact of being able to use only a single constellation.
- In addition, RAIM is not suitable to address system feared events affecting multiple satellites or even the entire constellation.
- RAIM is only suitable for snap-shot algorithms and therefore it makes difficult to extend its usage to hybridisation or Kalman filter approaches.

3.2.3.2.2 ARAIM

Advanced RAIM (ARAIM) extends RAIM to other constellations beyond GPS. ARAIM enables the use of the newer GNSS constellations to provide better levels of performance than RAIM with GPS alone. It also uses dual-frequency measurements for enhanced vertical positioning reliability.

ARAIM is a GNSS Integrity Technique at User Level which uses support integrity information disseminated by the GNSS core constellations and the Integrity Support Message (ISM), that is determined on the ground and broadcast to the airborne fleet. ARAIM is an evolution of the RAIM techniques and has been developed considering DFMC environment with the goal to protect multi-constellation users by means of a robust user integrity algorithm. Since Civil Aviation applications are the drivers for the development of ARAIM concept, ARAIM intends to provide a service for stringent aviation operations such as LPV-200.

The concept of ARAIM and the user algorithms were initially studied in the US in the frame of the GNSS Evolutionary Architecture Study (GEAS) [RD.11] and [RD.16] aiming at the definition of seamless air navigation worldwide based on GNSS for various aircraft operations and take advantage of the DFMC environment.

ARAIM architecture is based on a relatively simple ground infrastructure since the user algorithm can deal with part of the integrity assurance. To advance towards the common understanding, definition, and standardization of the ARAIM concept, the EU/US Working Group C fosters the coordination between the main stakeholders in the subject, mainly EC/ESA (EU) and GEAS (US). Over the last years, it was intended to clearly define how the ARAIM concept would work. Three reports were developed by the group to describe the concept and its architecture ([RD.17], [RD.18] and [RD.19]).

By design, the baseline ARAIM user algorithm can tolerate (if not detect and remove) a number of faulty satellites, meaning that even in the presence of certain number of faults it can still provide the required level of integrity. This allows relaxing the requirements of the ground segment, in particular in terms of time to alarm, which has a considerable impact on cost and complexity of the ground infrastructure and at the same time reduces the connectivity risk, which so far has been the greatest technical obstacle to the deployment of systems providing global GNSS integrity (rather than local or regional).

Solution separation computations presume one or more GNSS satellites may be faulty, and they iteratively compute multiple position solutions comprised of subsets of the n satellites in view (n, n-1, n-2, and so on) to ensure that at least one of the solutions is fault-free. Using assumptions on the nominal and faulted uncertainty of the solutions, the software can compute conservative horizontal and vertical protection levels (PLs) by bounding the uncertainty from all the solutions. This assures (to a targeted level of probability) that the user position is contained within these limits.

Multiple Hypothesis Solution Separation (MHSS) [RD.40] is the baseline algorithm for Advanced Receiver Autonomous Integrity Monitoring (ARAIM), where a solution is considered safe when the faulty measurement is excluded, and the remaining subset pass the Fault Detection tests. A protection level is set to bound the fault-free protection levels form each of the individual subset solutions.

The user algorithm describe here is extracted from [RD.20] and [RD.21], the main functions are summarised in the following steps:

- **Covariance matrix (C) estimation.** C is defined as follows:

$$C_{int\,i,i} = \sigma_{i,URA}^2 + \sigma_{i,tropo}^2 + \sigma_{user,i}^2$$

$$C_{acc\,i,i} = \sigma_{i,URE}^2 + \sigma_{i,tropo}^2 + \sigma_{user,i}^2$$

  - $\sigma_{i,URA}$ is the standard deviation of the satellite orbit and clock errors of satellite $\boldsymbol{i}$ used for integrity.
  - $\sigma_{i,URE}$ is the standard deviation of the satellite orbit and clock errors of satellite $\boldsymbol{i}$ used for accuracy and continuity.
  - $\sigma_{i,tropo}$ is the standard deviation of the tropospheric delay
  - $\sigma_{user,i}$ The standard deviation of the receiver noise,

- **Computation of the Position solution.** The solution is obtained by means of a least square linear estimation

$$\Delta x = (G^T \cdot W \cdot G)^{-1} \cdot G^T \cdot W \Delta\rho$$

  - $\Delta \boldsymbol{x}$ is the Corrections of the receiver position and clock states
  - G is the Geometry Matrix in East North Up coordinates with a clock component for each constellation
  - W is the Weighting matrix defined as C^{-1}

- Δρ is the vector of pseudorange residuals bases on the location of the satellite and the position solution given by the previous iterations

- **Fault-tolerant positions and associated standard deviations and biases**. After the positioning and the fault detection and exclusion the receiver has to estimate the integrity parameters. Hence For each of the k subsets the algorithm computes the position solution $\boldsymbol{x}^{(\boldsymbol{k})}$, evaluates the differences with the all-in-view position solution $\boldsymbol{x}^{(\mathbf{0})}$and determines the standard deviations and the test thresholds. The reference algorithm is described in detail in [RD.20] and [RD.21].

$$\Delta x = x^{(k)} - x^{(0)} = \left(S^{(k)} - S^{(0)}\right)y$$

where

$$S^{(k)} = \left(G^T \cdot W^{(k)} \cdot G\right)^{-1} \cdot G^T \cdot W^{(k)}$$

- $\boldsymbol{y}$ is the vector of pseudorange residuals bases on the location of the satellite and the position solution given by the previous iterations

The variances of $\boldsymbol{x}^{(\boldsymbol{k})}{}_{\boldsymbol{q}}$, where index *q* = 1, 2 and 3 designate the East, North and Up components respectively. The variances are then given by:

$$\sigma^{(k)2}{}_q = \left(G^T \cdot W^{(k)} \cdot G\right)^{-1}{}_{q,q}$$

The nominal biases of the position solution $\boldsymbol{x}^{(\boldsymbol{k})}{}_{\boldsymbol{q}}$ is represented as:

$$b^{(k)}{}_q = \sum_i \left|S^{(k)}{}_{q,i}\right| b_{nom,i}$$

The variance of the difference, $\Delta\hat{\boldsymbol{x}}^{(\boldsymbol{k})}{}_{\boldsymbol{q}}$, between the all-in-view and the fault tolerant position solutions:

$$\sigma^{(k)}{}_{ss,q} = \left(S^{(k)} - S^{(0)}\right)C_{acc}\left(S^{(k)} - S^{(0)}\right)^T e_q$$

- e_q is denoted as vector whose q[th] entry is one and all others are zero

- **Solution Separation Threshold and Chi-square test:** This algorithm test the abnormal range error using two tests: a solution separation threshold ($\boldsymbol{T}_{\boldsymbol{k},\boldsymbol{q}}$) and chi square test ($\chi^2$). A suitable algorithm for this part is also described in detail in [RD.20] and [RD.21]. The results of the this step tt determines whether to continue with Protection Level calculation, attempt fault exclusion, or declare the HPL and VPL invalid.

- **Computation of Protection levels.** The results of this test produces the HPL and VPL

As in [RD.20] and [RD.21] the HPL computation is done by first computing protection level on the East and North coordinates HPL_q for q=1 and 2. Hence HPL_q is defined as the solution to the equation:

$$2Q\left(\frac{HPL_q - b_q^{(0)}}{\sigma_q^{(0)}}\right) + \sum_{k=1}^{N_{faults,modes}} P_{fault,k}\,Q\left(\frac{HPL_q - T_{k,q} - b_q^{(k)}}{\sigma_q^{(k)}}\right) = \frac{1}{2}PHMI_{HOR}\left(1 - \frac{P_{sat,not\ monitored} + P_{cont,not\ monitored}}{PHMI_{VERT} + PHMI_{HOR}}\right)$$

where:

- $P_{sat,not\ monitored}$ *and* $P_{cont,not\ monitored}$ *- the probability that a satellite or constellation is not being monitored at that epoch.*

- $PHMI_{VERT}$ *and* $PHMI_{HOR}$ *– the integrity allocations to the vertical and horizontal coordinates*

- Q *- The statistical Q function that gives the tail probability of a standard Gaussian distribution*
- T *- The test threshold*
- σ *- The variance calculated in the given direction*
- b *- The bias represents the worst case impact on the position solution*
- P_{fault} *- The probability of a fault occurring*

The horizontal protection limit requires an additional calculation to be fully formed, therefore the HPL is

$$HPL = \sqrt{HPL_1^2 + HPL_2^2}$$

The VPL is computed as follows:

$$2Q\left(\frac{HPL_q - b_3^{(0)}}{\sigma_3^{(0)}}\right) + \sum_{k=1}^{N_{faults,modes}} P_{fault,k} Q\left(\frac{VPL - T_{k,3} - b_3^{(k)}}{\sigma_3^{(k)}}\right) = \frac{1}{2} PHMI_{VERT} \left(1 - \frac{P_{sat,not\ monitored} + P_{cont,not\ monitored}}{PHMI_{VERT} + PHMI_{HOR}}\right)$$

The main critical points related to the ARAIM concept definition are:

- ARAIM assumptions and Feared Events: The ARAIM user algorithms need to make certain assumptions about errors and threats and requires certain information to be provided by a specific ground segment, in order to generate protection levels and provide integrity. In particular the user ARAIM algorithms requires values for the standard deviation of a distribution that bounds the orbit/clock error in the fault-free case and the nominal and maximum biases in fault-free conditions. A further important aspect is knowledge of the faults/failures that are addressed by the ground segment and remaining threats that are applicable for the user. Also relevant are the constellation wide faults.
- ARAIM architecture: Different ARAIM concepts might have different levels of ground monitoring and hence would imply different levels of fault detection by the ground segment. This would have a significant impact on the user ARAIM architectures in terms of their performance, and also on the design of the algorithm itself. Another relevant issue dependent on the ARAIM architecture design is the ISM dissemination. Three main architectures were considered:
    - Horizontal ARAIM
    - Offline ARAIM
    - Online ARAIM
- Once defined at high level the reference architecture of ARAIM, the key problem to detail the architecture was the dependence or coupling between the specification of the User Algorithm and the ISM infrastructure. Three aspects had to be carefully assessed: the identification of threats, the allocation of barriers and performance budgets along the ARAIM system and the user equipment, the drivers to specify the User Algorithm and the drivers to specify the ARAIM system.

In summary some identified advantages of ARAIM with respect to other technologies are:

- Dissemination of the information supporting the integrity assurance is disseminated in the GNSS SIS of all Satellites through the ISM. This represents a clear advantage with respect to SBAS, in which the integrity information is disseminated in the SIS of few GEO satellites, which implies visibility problems in harsh environments such as Urban in which it could happen that the integrity information does not arrive to the user by the blockage of SBAS signals by the buildings and thence, unavailability of the integrity service.

- ARAIM provides a global service, as opposed to GBAS which provides a local service within a radius of 40km and thence, GBAS cannot be considered as a suitable technology for covering wide areas due to the large investment associated to populate the area with many GBAS systems.
- ARAIM provides a certain level of protection against local effects, which is especially important in the typical environments of non-aviation applications. In addition, ARAIM is able to handle wide constellation failures or multi-satellite failures.
- ARAIM algorithm may be adapted to run into Kalman filtering engines
- ARAIM is a suitable integrity technique for DFMC environment as opposed to RAIM in which the hypothesis of single failure prevents its use for augmenting various constellations and frequencies. This implies that ARAIM would provide better performances than RAIM and more resilience upon interferences.
- In addition, RAIM detection of a failure is instantaneously while for SBAS/GBAS there is a Time-To-Alert (TTA) of up to 6 seconds.

Some identified limitations of ARAIM with respect to other technologies are:

- ARAIM user algorithms needs to make certain assumptions about errors and threats and requires certain information to be provided by a specific ground segment, in order to generate protection levels and provide integrity. Although this information has a much lower update rate than SBAS or GBAS, the dissemination of no information at all may make models and assumptions tend to be very conservative and performances may be too poor in terms of PL.
- One of these assumptions is that measurement errors not excluded follows a biased Gaussian distribution, which is not always true for all circumstances. This may cause that in some operations the integrity of the RAIM algorithm may be compromised.
- ARAIM is a computationally demanding algorithm compared to classical RAIM.
- Finally, is clearly insufficient for use-cases where the confidence levels must be very stringent due to the conservative assumptions that causes large PLs.

3.2.3.3 Comparison and conclusions

Table 3-3 summarises the main conclusion about the different aviation integrity concepts described.

Table 3-3. Summary of integrity concepts

Integrity concept	High level concept	Maturity	Applicability	Limitations
Classical RAIM	User Level integrity	High	■ Needs no ground infrastructure and no information dissemination ■ Global service ■ Certain protection against local effects as far as single-failure and error characterisation	■ Conservative assumptions make performances may be too poor for the Maritimes domain ■ Measurement errors not excluded are assumed to follow a biased Gaussian distribution

Integrity concept	High level concept	Maturity	Applicability	Limitations
			assumptions are deemed acceptable ■ Instantaneous failure detection	■ The single failure assumption cannot be accommodated in the DFMC trend ■ Not suitable to address system feared events ■ Only suitable for snap-shot algorithms ■ Insufficient for very stringent confidence levels cases
ARAIM	User Level integrity	High	■ Dissemination of integrity information by GNSS SIS of all Satellites ■ Global service. ■ Certain protection against local effects ■ Certain protection against constellation and multi-satellite failures effects ■ May be adapted to KF engines ■ Suitable for DFMC techniques ■ Instantaneous failure detection	■ Needs to make assumptions about errors and threats, and to maintain these hypothesis, following the GNSS constellation evolution ■ Requires certain information to be provided by a specific ground segment (online concept). ■ Dissemination of no information at all (off-line concept) may make models and assumptions tend to be very conservative ■ Measurement errors not excluded are assumed to follow a biased Gaussian distribution ■ Computationally demanding algorithm ■ Insufficient for very stringent confidence levels cases
SBAS	System Level integrity	High	■ Technique well mature, extensively used, tested and properly standardized for civil aviation ■ Able to deal with any kind of system level failure, as well as constellation failures. ■ Able to detect some local effects for small areas such as interferences or atmospheric perturbations. ■ Regional systems already deployed in the most populated landmasses and coastal areas. ■ Usually provides relatively good performances in terms of accuracy and PLs size	■ Not able to tackle local effects and the local environment is modelled. ■ Detection of a failure is not instantaneously and there is a Time-To-Alert (TTA) of 6 seconds.

3.3 GNSS Performance Requirements for Maritime

Most integrity systems and integrity algorithms have been developed and designed for the aviation domain. However, other user communities exist, such as maritime, and have different demands in contrast to the aviation community. The previous section looked at Integrity as it relates to aviation, this section will look at the current GNSS performance related requirements for maritime. These define the standards against which the navigation solution is judged acceptable to the mariner.

3.3.1 IMO Resolution A.915(22)

The IMO Resolution A.915(22) [RD.25] focuses on GNSS as a stand-alone system and introduces the "*maritime requirements for a future GNSS*", which was adopted on 29 November 2001. It provides operational requirements based on the actual performance at the user level (in contrast to IMO resolution A.1046(27), which is provided at the system level). These requirements are expressed in terms of accuracy, integrity, continuity, and availability similarly to how they are defined by the RTCA for civil aviation, which consider both system-level and user-level performance.

It is the first regulation that provides a definition for integrity terms:

"

- *Integrity. The ability to provide users with warnings within a specified time when the system should not be used for navigation.*
- *Integrity monitoring. The process of determining whether the system performance (or individual observations) allow use for navigation purposes. Overall GNSS system integrity is described by three parameters: the threshold value or alert limit, the time to alarm and the integrity risk. The output of integrity monitoring is that individual (erroneous) observations or the overall GNSS system cannot be used for navigation.*
  - *Internal integrity monitoring is performed aboard a craft.*
  - *External integrity monitoring is provided by external stations.*
- *Integrity risk. The probability that a user will experience a position error larger than the threshold value without an alarm being raised within the specified time to alarm at any instant of time at any location in the coverage area.*

"

The end user requirements listed by IMO Resolution A.915(22) [RD.25] are summarised in Table 3-4

Table 3-4 IMO Resolution A.915(22) User Requirement [RD.25]

	System level Parameters				Service level Parameter			
	Absolute Accuracy	**Integrity**			**Availability % per 30 days**	**Continuity % over 3 hours**	**Coverage**	**Fix Interval (s)**
	Horizontal (m)	**Alert limit (m)**	**Time to alarm (s)**	**Integrity risk (per 3 hrs)**				
Ocean	10 (100)[4]	25	10	10^{-5}	99.8	N/A	Global	1
Coastal	10	25	10	10^{-5}	99.8(99.5)	N/A (99.85)	Global	1
Port Approach and restricted water	10	25	10	10^{-5}	99.8(99.8)	99.97 (99.97)	Regional	1
Port	1	2.5	10	10^{-5}	99.8	99.97	Local	1
Inland waterways	10	25	10	10^{-5}	99.8	99.97	Regional	1

This resolution is not enforced, it simply sets the projected requirements for a future GNSS system. It should also be noted that due to these requirements being recognised as 'out-of-date', there have been several aspects subject to updates. Most notably, the continuity service level parameter of IMO A.915 is shown over a duration of three hours, where it is now accepted by the maritime community that 15 minutes is a more reasonable duration. This is reflected in more recent resolutions as is shown in IMO Resolution A.1046(27) [RD.26].

In addition to that, it should be noted the integrity risk is proposed also for a duration of three hours. This means, that assuming the same measurement correlation as aviation of 150s, integrity risk is equal to $1.4 \cdot 10^{-7}$ per independent sample. This requirement is very close to aviation which seems too stringent for maritime general navigation. It is accepted in the maritime community that the requirement is subject to modification reducing the duration to a more reasonable 15 minutes. Therefore, the integrity risk would be around $1.7 \cdot 10^{-6}$ per independent sample.

The main issue with these requirements though is that they were proposed as examples of future requirements that might apply if an aviation style integrity approach were adopted, but without necessarily assessing whether the integrity parameters and the values associated with them were relevant or suitable for maritime operations. This means there is an inherent risk in taking these parameters and values as a basis for designing and testing maritime integrity algorithms - an algorithm could be developed and tested to satisfy these requirements, without necessarily being useful to the mariner.

3.3.2 IMO Resolution A.1046(27)

The IMO Resolution A.1046(27) [RD.26], was adopted on 30th November 2011, as a further updated resolution of IMO Resolution A.915(22) [RD.25]. This resolution describes the performance requirements for a global radionavigation at the system level. For the system provider it defines the procedures and responsibilities concerning the recognition of the system, typically for GNSS. It also sets overall requirements for the shipborne receiving equipment.

Specifically, the resolution indicates that a generic component needs to fulfil two tasks: firstly, it must provide the users with navigation signals; and secondly, it must also constantly monitor the quality of the navigation service provided (i.e., the "system integrity monitoring" task), and send the integrity information to the user together with the navigation signals. Regarding this integrity monitoring, it is specified that:

[4] Figures in bracket refers to operational requirements according to Red. A.953

"*An integrity warning of a system malfunction, non-availability or discontinuity should be provided to users*."

With this approach, the users are warned that the system should not be used if a failure is detected in one of the navigation modules.

The resolution considers two different navigation phases, for which accuracy, integrity, signal availability and service continuity requirements are provided. Therefore, the radionavigation system should be able to meet the minimum performance listed in Table 3-5.

Table 3-5: IMO A.1046(27) requirements summary [RD.26]

Requirement	Ocean waters	Harbour entrance, harbour approaches and coastal waters
Accuracy: 95% horizontal navigation system error	<=100m	<=10m
Integrity: "An integrity warning of a system malfunction, non-availability or discontinuity should be provided to users…"	*"As soon as practicable"*	*"within 10s"*
Signal **availability**[5]	> 99.8%	> 99.8%
Service **continuity**	N/A	*"The system shall be considered available when it provides the required integrity for the given accuracy level. When the system is available, the service continuity should be ≥99.97% over a period of 15 minutes."*

This is a regulation that comes into force since IEC standards make reference to it for performance validation. However, it is recognised by the maritime community that the list of integrity requirements is vague and leaves the door open to any implementation not guaranteeing navigation safety. In contrast, the IMO Resolution A.915(22) [RD.25] recognises that further parameters are needed to fully characterise and design a robust integrity monitoring mechanism. Some of the parameters to be defined are:

- Maximum False Alarm probability. This parameter will guarantee continuity, although it could be derived from the service continuity requirement
- "System malfunction, non-availability or discontinuity". This is a very vague term and needs to be defined. From IMO Resolution A.915(22), this could correspond to:
  - Integrity Risk. The probability that a user will experience a position error larger than a threshold value without an alarm being raised within the specified time to alarm at any instant of time at any location in the coverage area.
  - Alarm Thresholds. Limits in position or measurement domain that triggers the an alarm.
  - Time to Alarm. Maximum time affordable between the error occurrence and the user is warned.

3.3.3 IMO Resolution MSC.401(95)

The Maritime Safety Committee (MSC 95) , via resolution MSC.401(95) [RD.27], adopted the Performance Standards for Multi-system shipborne radio-navigation receivers which provide the basis to enable the full use of relevant data originating from current/future radio-navigation system/services (e.g. range measurements, system parameters and variables such as

[5] Let us remark that IMO A.1046(27) does not specify the time window of the availability requirement, whereas IMO A.915(22) sets a 30-day period.

ephemeris, corrections, augmentation data), with the provision that associated PNT Guidelines are to be developed.

As stated in the resolution, the introduction of multi-system shipborne navigation receiver performance standards will allow the combined use of current and future radio navigation and augmentation systems for the provision of position, velocity, and time data within the maritime navigation system.

The resolution considers GNSS-based radio navigation to obtain resilient PVT solutions:

- A multi-system receiver using navigation signals from two or more GNSS, with or without augmentation, provides improved position, velocity, and time (PVT) data. Improved resistance to intentional and unintentional radio frequency interference is achieved when two or more independent or frequency diverse radio-navigation systems are used. Such a combined approach provides redundancy to mitigate the loss of a single system.
- Receiver equipment, capable of combining measurements from multiple GNSS and an optional terrestrial radio-navigation system, with or without augmentation, to form a single resilient PVT solution, can be used for navigation purposes on ships of speeds not exceeding 70 knots

One of the main operational requirements is the provision of PVT data with the necessary level of resilience and integrity, whether it is used directly as input to other equipment or provided for use within Integrated Navigation Systems (INS). This MSC.401(95) [RD.27] resolution references IMO resolutions A.1046(27) and A.915(22) regarding the provision of that accuracy, resilience, and integrity performances.

This resolution defines the requirements in a modular fashion: receiver equipment requirements, operational and functional requirements, interfacing and integration requirements, and documentation requirements. For further details please refer to [RD.26].

3.3.4 IMO Resolution MSC.1575(1)

The purpose of the IMO Resolution MSC.1575(1) [RD.28], as auxiliary material of the IMO Resolution MSC. 401(95) [RD.27], is to enhance the safety and efficiency of navigation by improved provision of position, navigation and timing (PNT) data to bridge teams (including pilots) and shipboard applications (e.g. AIS, ECDIS, etc.).

These Guidelines aim to establish a modular framework for further enhancement of shipborne PNT data provision by supporting:

1. consolidation and standardization of requirements on shipborne PNT data provision considering the diversity of ship types, nautical tasks, nautical applications, and the changing complexity of situations up to customized levels of support;
2. the identification of dependencies between PNT-relevant data sources (sensors and services), applicable PNT data processing techniques (methods and thresholds) and achievable performance levels of provided PNT data (accuracy, integrity, continuity and availability);
3. harmonization and improvement of onboard PNT data processing based on a modular approach to facilitate changing performance requirements in relation to nautical tasks, variety of ship types, nautical applications, and under consideration of user needs (SN.1/Circ.274);
4. the consequent and coordinated introduction of data and system integrity as a smart means to protect PNT data generation against disturbances, errors, and malfunctions (safety) as well as intrusions by malicious actors; and
5. standardization of PNT output data including integrity and status data.

Performance requirements on each set of PNT output data are described in terms of accuracy and integrity, whereby several levels are specified to address the diversity of operational as well as technical requirements.

Numbers and thresholds of operational and technical performance levels per PNT data type should be compliant with existing performance standards and resolutions, and the introduction of technical performance levels (A.1, A.2, B.1, B.2, …) it paves the way for enabling a graduated specification of task- and application-related requirements on PNT data. Furthermore, it prepares a need-driven evaluation and indication of accuracy.

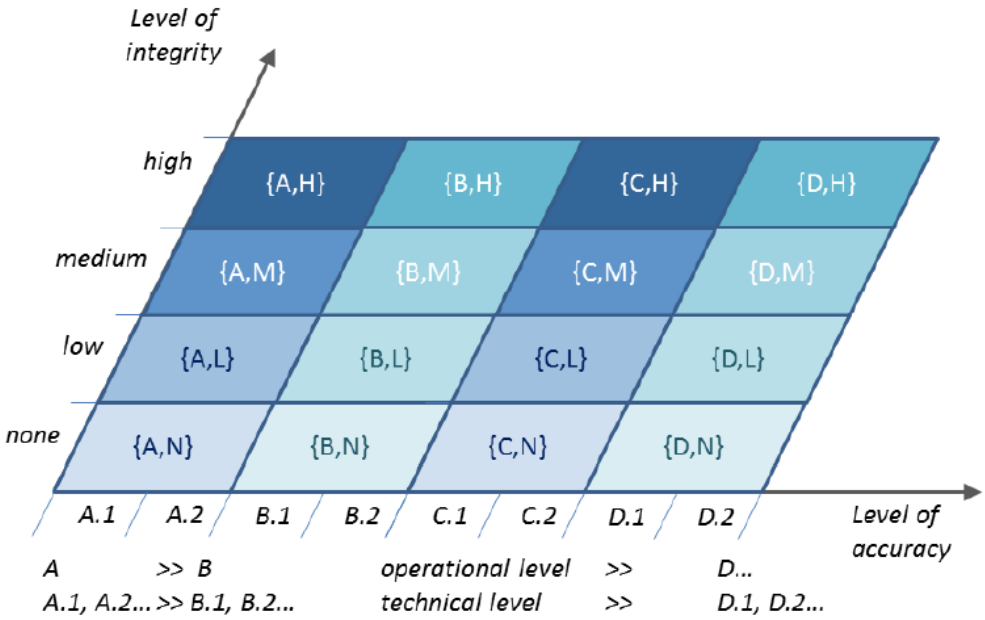


Figure 3-15. Generic performance level for each PNT output data in relation to accuracy and integrity [RD.28]

Integrity data per each individual PNT output data should be provided to indicate the further usability of data. The value of included integrity information depends on applied principles of integrity evaluation in relation to a dedicated accuracy level:

- None: Unavailable integrity evaluation.
- Low: Integrity evaluation based on plausibility and consistency checks of data provided by single sensors, systems, services, or sources.
- Medium: Integrity evaluation based on consistency checks of data provided by different sensors, systems, services, and sources with uncorrelated error parts as far as possible.
- High: Integrity evaluation based on estimated accuracy (protection level).

The purpose of this is to achieve standardized and integrity evaluated PNT output data to enhance user awareness regarding achieved performance level. As any guidelines, these are only IMO recommendations, and their usage is not enforced.

3.3.5 IEC 61108 series of standards

The IEC 61108 series of standards provide performance requirements, methods of testing and required test results for Maritime Global navigation satellite systems (GNSS) receiver equipment. The series consists of several parts:

- Part 1 [RD.29]: GPS, covering the performance standards in MSC.112(73)
- Part 2 [RD.30]: GLONASS, covering the performance standards in MSC.53(66)[6]

[6] IEC 61108-2 (first, and up to date, latest version) was published in 1998 and it recalls to the applicable GLONASS Performance Standard resolution to date, which is the MSC.53(66). A more recent version of this resolution, IMO MSC.113(73) was adopted in 2000

- Part 3 [RD.30]: Galileo, covering the performance standards in MSC.233(82)
- Part 4 [RD.32]: DGPS and DGLONASS, covering the performance standards in MSC.114(73)

Each of the standard parts covers one of the main GNSS constellations, and the fourth part covers differential GNSS with GPS and GLONASS. Each of them has a direct relation to a corresponding IMO resolution that defined the performance standards for that specific GNSS, a combination of GNSS, with or without differential, shipborne receiver equipment. Currently, no SBAS equipment performance standards exist, however, these are planned to be in place by 2023/2024, as part of the development of the IMO MSR performance standard. In addition, there is a reference to SBAS, and EGNOS specifically, in Part 4 [RD.32] which states that:

"*Additional functionality (e.g., use of differential corrections and integrity, from multiple beacon reference stations, Eurofix, LORAN-COMM, VTW, FM subcarrier, commercial satellite, WAAS, EGNOS, MSAS and RTK) is permitted if the manufacturer can demonstrate this does not degrade performance.*"

This means that EGNOS may be used as a source of differential corrections and integrity if it can be demonstrated that performances are not degraded (concerning DGPS performance standard). The way EGNOS is used and how it affects performances is not yet detailed in the standard, and it may not be straightforward. However, SBAS performance standards are being developed; therefore, suitable receivers can be developed and evaluated once in place.

Regarding the provision of integrity, these standards assess the capability of the receiver to provide an indication if the position is likely to be calculated outside of the requirements of the performance standards. This definition does not constrain the specific RAIM algorithm implementation deliberately to let the manufacturers implement the most suitable one for their applications.

Classical RAIM algorithms may use redundant information for simple positioning error detection, may exclude a faulty measurement, and may compute a position error bounding similar to Protection Level (PL) concept. Maritime users may use a combination or any other type of algorithm. In their annexes, IEC 61108-1 [RD.29] GPS and IEC 61108-3 [RD.31] Galileo standards provide guidelines on the algorithm to implement and how to configure it.

The proposed implementation matches the definition of Classical RAIM used for decades in aviation. Nevertheless, their proposed algorithm is different since GPS only proposes an FD algorithm while Galileo proposes an FDE plus a Protection Level calculation algorithm. This implies that the concept of HAL is not covered in the IEC 61108-1 [RD.29] GPS standard since the computation of a protection level is not contemplated either.

In addition, the parameters to configure each RAIM do not match, since the probability of false alarm and miss detection stated on GPS IEC standard is much more relaxed than Galileo one.

Para-meters	Description	RTCA NPA-GPS	IEC 61108-1:2003 GPS	IEC 61108-3 Galileo
R_{FD}	False alert rate	10^{-5}/h	10^{-4}/h	10^{-4}/h
P_{FD}	Probability of false detection	$3 \cdot 10^{-7}$	$5 \cdot 10^{-2}$	$3 \cdot 10^{-6}$
P_{MD}	Probability of missed detection	10^{-3}	$5 \cdot 10^{-2}$	$1 \cdot 10^{-3}$
P_{WE}	Probability of wrong exclusion	10^{-3}	-	$1 \cdot 10^{-3}$
P_{FE}	Probability of failed exclusion	10^{-3}	-	$3 \cdot 10^{-2}$
TTA	Time to alert	10 s	10 s	10 s

Table 3-6. RAIM FDE parameters comparison.[RD.42]

To prove that a receiver is compliant with the requirements specified in this standard, two simple tests are proposed. The first one intends to evaluate the performance of the receiver under safe and cautious states, and the other one evaluates the unsafe state. Both tests only check the allowed elapsed time since something causes a change in the integrity status (by a change in the number of satellites or their behaviour) until it is displayed in the integrity monitoring.

The lack of detailed test parameters definition is clearly deficient in terms of safety. The error introduced in the test should be quantified or at least limited. In addition, there are not any procedures to check if the implemented RAIM is correctly considering the probability of miss detection and false alarm.

Considering the simplicity of the tests, which do not even assess the probabilities of miss-detection or a false alarm, there is no assurance that the RAIM algorithm implemented in the receiver correctly provides system-level integrity. To ensure this, it would be necessary to improve the test method to characterize the value of the introduced errors and add new tests to evaluate the complete set of requirements to the implemented integrity algorithm.

Nevertheless, laboratories that perform the test have their own internal rules to determine whether a receiver passes the RAIM test or not,

It shall be remarked that these tests only consider a single satellite failure at a time although some algorithms are able to detect multi-failure or even the failure of the entire constellation. These capabilities are not evaluated and therefore it shall be not assumed that they are safe under these conditions.

3.3.6 Conclusions on Maritime Integrity Requirements

These sets of requirements have in common the fact that there is no need for the vertical position component. This fact certainly represents a clear aspect that distinguishes maritime from the aviation domain. This fact impacts the design of the integrity algorithms but there are other more relevant considerations to be made about the understanding of integrity and its definition.

The next table summarizes the definitions of integrity in different maritime resolutions (see [RD.33] for detailed information).

Table 3-7 Integrity definition in the maritime domain

Source	Definition	Remarks
IMO resolution A.915(22)	"The ability to provide users with warnings within a specified time when the system should not be used for navigation"	Performance requirements at user level. Therefore, integrity monitoring must be performed at user level. Integrity defined by three parameters: alert limit, time to alarm and integrity risk, aligned with ICAO. Considers the implementation of protection levels that overbound position errors at certain integrity risk. Not mandatory regulation, it's a forecast from 2001 of expected needs in the future. Some requirements are too stringent and may be out of date
IMO resolution A.1046(27)	"Integrity warning of system malfunction, non-availability or discontinuity should be provided to users"	Integrity monitoring is considered at a 'system-level' scope, meaning that the user will not be warned of potential performance degradations fur to local error sources. This resolution does not specify any requirement or an associated integrity risk to be covered, it means, the target level of service.
IALA Guideline 1112 (DGNSS)	"The ability to provide users with warnings within a specified time when the system should not be used for navigation"	DGNSS Integrity Monitoring checks in the signals and position domain to provide some integrity alarms upon system malfunctions. In line with IMO A.1046(27)

Source	Definition	Remarks
IMO resolution MSC.401(95).	"Be capable of assessing whether the performance of the PVT solution (e.g. accuracy and integrity) meets the requirements for each phase of navigation11. An alert should be provided when such assessment cannot be determined"	References IMO resolutions A.1046(27) and A.915(22) regarding the provision integrity performances. Definition of integrity does not agree 1046(27) and A.915(22)
IMO resolution MSC.1575(1). NCSR Guidelines for the MSR	"The ability to provide users with information within a specified time when the system should not be used for navigation including measures and/or indicating trust" (derived from resolution A.915(22))	From a technical point of view there are some aspects related to integrity/safety that are not rigorously defined and that could imply a risk of interpretation with respect to the use of GNSS and to GNSS integrity capabilities. It paves the way for enabling a graduated specification of task- and application-related requirements on PNT data defining several levels of integrity and accuracy. Aims to achieve standardized and integrity evaluated PNT output data to enhance user awareness regarding achieved performance level

As seen from the assessment of current requirements, there are several gaps and ambiguities when it comes to integrity in the maritime domain.

Firstly, the current regulations that are in force (such as IMO resolution A.1046 (27) [RD.26]) are linked to system integrity, such as DGPS. It means the integrity monitoring system provides alerts to the user in case it is detected that the GPS system information should not be trusted. However, this does not strictly cover user level integrity and all the additional faults that may exist for a receiver on a vessel that are not common to a shore based integrity monitoring site.

For user level integrity, any notion of what constitutes a 'system malfunction' or 'when the system should not be used for navigation' are vague. There are 95% accuracy requirements, but this is not a threshold for instantaneous fault detection / alerting as 5% of errors are expected to be bigger than such a threshold. As seen in aviation, there are well defined values for the alert limits and integrity risk for each type of operation, and thorough analysis of different faults and probabilities. In maritime however this is not currently available. IMO resolution A.915 (22) [RD.25] made an attempt to look at such values, but these requirements were written in 2001 as a guess of future needs, and there were already known errors within them (such as 3hrs rather than 15min continuity time) and with the advent of new constellations and operations they are out of date and require revision.

This is also the approach of the test and integrity algorithms required in the IEC standards, where an alarm is required for faulty situations. However, the tests proposed by IEC standards are vague and not well defined in terms of the detailed set-up and steps of the test and the exact pass/fail criteria. With the current definition a receiver may pass if it flags a fault eventually – no matter if it actually protects the user against a faulty position. In addition, those requirements that are proposed as examples of implementation in IEC standards do not agree for different constellation like GPS and Galileo.

Therefore, could be concluded that integrity scheme is not clear in maritime regulation and no direct requirements are available, except the need to raise alarms at the presence of faults. This relies in the assumption the pilot is liable to collect all the navigation information available by any means and decide what to do.

3.4 Maritime vs Aviation Differences

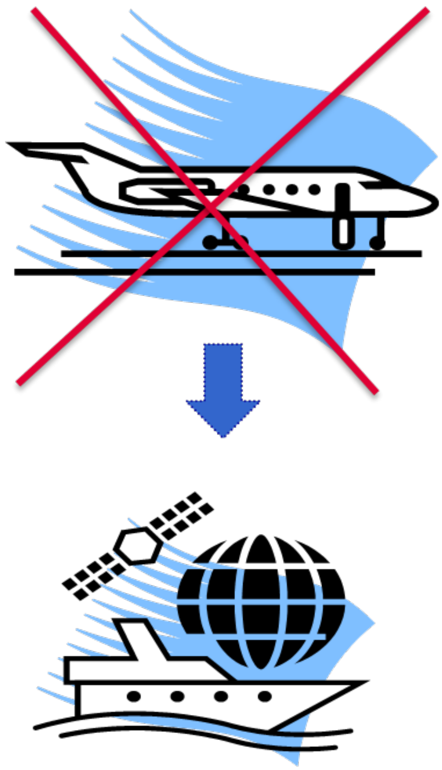
In previous sections, the current state of integrity concepts and requirements for aviation maritime was assessed. In this section, other differences between the current state of play in maritime and aviation with regards integrity are discussed.

3.4.1 Understanding of Integrity and Risk

Civil aviation has traditionally been the driver for the development of the GNSS integrity concept. However, it is important to highlight as concluded in previous sections the concept of integrity is different for the Maritime community.

The need for resilience and integrity (R&I) of maritime (and wider sector) Positioning, Navigation and Timing (PNT) is required to ensure safe navigation within the maritime environment. Throughout this document the term Integrity, has been defined in both the aviation and maritime sectors, and it have been observed that the definitions are closely aligned.

However, the aviation safety approach cannot be directly used in the maritime sector.



For aviation, there are well defined concepts, procedures, allocation and understanding of failure risk. The main reason of this stringent and extensive regulation is that several key processes for flight safety take the navigation information as inputs and the risk of accident is required to be allocated in a top-down approach. Therefore, aviation needs the definition of a standardisation scheme for navigation systems, including receivers. Each of these receivers to be placed on a plane needs to pass several tests that check its design, manufacture, installation, and environmental limits.

Alternatively for the maritime current situation, the mariner makes the final decision on navigation, looking at information from multiple sensors, charts and also visual aids. The failure probability allocation has never been considered in this scheme since the pilot is liable for the safety of the vessel. Navigation systems have been always considered as an aid more than a critical system for the safety. Because of that, integrity is understood as an indication (without any specific strong requirement) that the system is working as expected. Finally, the availability of several sources of information may overwhelm mariners, and that is the reason simple and interfaces as traffic light concept is essential.

However, in future with autonomous vessels, integrity will become important as the dependency of the navigation system increases. For pilotless or remotely piloted vessels, the level of risk or liability must be clearly allocated, and its implementation should be somehow validated. So, it is anticipated that both concepts will converge to the aviation one, as have happened in other domains like rail or road.

There are different safety concepts on the table: SBAS aviation-like, IMO safety concept, NCSR multi-system concept, etc. There is a risk that the straight-forward application of an SBAS-like concept is not suitable for the maritime community and/or is not in line with the ones proposed in the maritime community. Therefore, special attention must be paid to understanding maritime community safety needs and timeframe considering SBAS/aviation design considerations and translating them in terms of integrity. Maritime regulation takes long periods of time to be modified and it is not proposed any change until there is a real need. Because of that, it is expected a minor evolution of the integrity concept in maritime domain for manned vessels, exploring new systems and hybridisation but not introducing significant changes at regulatory level. Nevertheless, a different perspective is required to address the future autonomous vessels.

Finally, there is a key difference between IMO and ICAO standardisation scheme. In aviation, there are a well-established regulatory framework with many institutions related each of them with a clear role in terms of regulation development, certification, inspection, licenses issue and punitive capacity. There is not that clear structure available in the maritime domain, where IEC test and wheel mark stamp are the most similar procedures.

3.4.2 Maritime operative vs aviation

In manned aviation, there are few aircraft configuration possible, environments and operations are quite limited. However, diversity of marine operations, types of vessels, infrastructure and environments is much higher.

For aviation, there are several conditions which simplifies the situation for a precision CAT-I operation compared to the daily life in maritime operations. Some of them are listed below:

- A CAT-I approach is a well-defined operation (flight path, velocity, operational thresholds, ATONs, etc.) with little room for deviations
- A CAT-I is performed under regulated environments on an airport
- A CAT-I approach is limited in duration,
- The installation of GNSS antennas and receivers on airplanes are following strict guidelines and procedures and all of them are certified.
- The environment on an airport is near ideal with regards to avoiding multipath and other obstructions.
- No expected other aircraft in the surroundings since air traffic managements preserve separation.
- If bad weather, the aircraft can usually go to another airport.

Therefore, as a summary of the operational conditions' comparison between aviation and maritime, it can be concluded that aviation context has a very definite operational framework of standards, with detailed and specific procedures for each phase of flight and situation. This situation is completely different in maritime.

In addition to the aforementioned conditions, the requirements for each particular flight phase and type of approach are well defined have a clear relationship with tolerable hazard risk of collision and the definition of the airspace. In maritime, there is a much wider range of operations, for example in navigation in harbour entrances, harbour approaches and coastal waters, and all of them have the same performance requirements. This means the same system could comply with performance requirements in some operations and not others.

Finally, a difference between maritime and aviation gets obvious when comparing the exposure periods over which integrity and continuity are specified. While in aviation are defined over an exposure period of 150 seconds for integrity and 15 seconds for continuity, in maritime defines its exposure periods consistently over 15 minutes. This will have implications on the threat modelling for the maritime user: for integrity and continuity the number or type of events to be considered in 15 seconds or in a 15 minutes period is different.

3.4.3 Maritime Environmental Conditions

As discussed previously, in aviation, there are specific operations, well described and common for most flights. However, for marine operations, there is a more complex variety of operations, types of vessels, infrastructure and environments, requirements of navigation equipment on-board for different types of vessels, education of captains and masters and length of operations. Typical operations for vessel include:

- The Ocean Phase: It can also be classed where position fixing by visual reference to land, to fixed or floating aids to navigation is not possible.
- Coastal navigation is classified as where the distance from the coast is 50 nautical miles or less or at the limit of the continental shelf (where the depth is approximately 200m), whichever is greater. The principal uses of navigation systems in this phase of voyage are associated with maintaining safety.
- Port approach and restricted waters: This phase is classified where the freedom to manoeuvre is limited, and it is often necessary to keep to specific channels or separate traffic routeing measures, taken according to channel width, under keel clearance and local conditions The need for frequent manoeuvring, close to other vessels and grounding mean that navigation requirements are more stringent than for the coastal phase and may require three dimensional position fixing, depending on local circumstances e.g. whether channels are shallow compared to draught of the vessel.
- Docking/Port: This phase is the final phase of arrival and consists of bringing the ship alongside the berth. The major risk during this stage is to hit the docking facility with more speed than required and therefore to cause significant damage to dock and ship. These surrounds are not conducive to positioning using radio-navigation aids. They often contain large structures that can obscure signals and large metallic objects that can cause multipath, plus problems caused by electromagnetic interference.
- Inland waterways: Inland navigation is typified by operations involving large, slow vessels in high traffic areas with limited manoeuvrability. Cargoes can include commercial, perishable, and industrial loads. Inland navigation covers all aspects of navigating on inland waterways including rivers, lakes, canals, ports, quays and wharfs. It may also involve navigating locks and other river infrastructures.

In these operational modes GNSS is the common source of Positioning, Navigation and Timing (PNT) data on-board a vessel. GNSS is being used both for safety and business-critical applications and for non-critical leisure use [RD.34]. In this context, GNSS is playing a key role and for this reason it is necessary to characterise the main environmental conditions related to satellite navigation, which are detailed in this section.

GNSS error sources that affect the performances of the overall system are depicted in Figure 3-16. This figure summarises the system-dependent errors and their typical order of magnitude. Besides, the pseudorange scheme shows errors that depend on the receiver, as the receiver clock offset and the receiver instrumental delay. Although these errors could not be considered as part of system errors, they are also described because they will be present for every user.

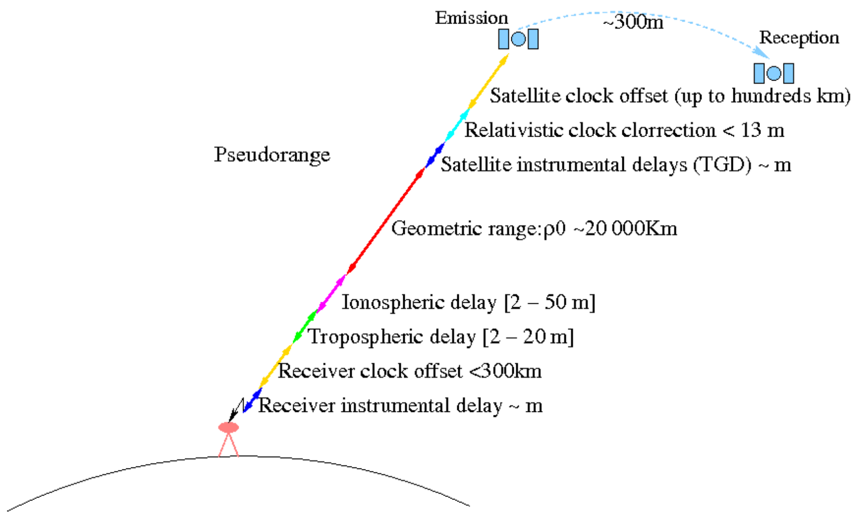


Figure 3-16 Pseudorange measurement content [RD.3]

These errors could be minimised or even suppressed by correction techniques. In addition, some of them could be modelled with a physical-mathematical model and, once these models are tuned, their behaviour could be predicted. SBAS systems, for example, EGNOS, provide corrections for most of the components detailed in the figure and have over-bounding error models for the effects not related to the system.

In the maritime domain error such as atmospheric model (ionosphere, troposphere, etc.) do not require specific adaptation to the maritime environment. The error models associated with these errors are have been extensively tested and widely used outside of the maritime domain. However, there are local effects, which includes but are not limited to multipath events, unintentional and intentional interference, which can significantly degrade GNSS performances. These effects influence the operation of the GNSS in the maritime domain at the user level differently than in aviation and hence the existing local error models may not be valid to safely represent these error contribution

3.4.3.1 Multipath Error

GNSS signals are reflected by many natural and constructed objects, including buildings, walls, other vessels, and the ground. Glass, metal, and sea surfaces are particularly strong reflectors. Reflected signals can be picked up by the GNSS receiver and interfere with the reception of signals coming directly from the satellite, see Figure 3-13. The phenomenon of receiving both the direct signal and reflected echoes is referred to as multipath. When the direct signal is blocked, and only the reflected signals are received this is referred to as Non Line Of Sight (NLOS), which is further discussed below.

Two kinds of multipath exist: specular multipath from direct reflections off smooth surfaces and diffuse multipath resulting from scattering and sources of diffraction. Low-elevation angle signals are more likely to receive reflections by vertical surfaces than high-elevation angle signals.

Where multipath interferes with directly received signals, the reflected signals distort the code correlation peak within the receiver. As a result, the code phase (used to generate the pseudorange) of the direct line-of-sight (LOS) signal cannot be accurately determined by equalizing the power in the early and late correlation channels. The magnitude of the resulting code-tracking error depends on the path delay of the reflected signal with respect to the direct, the relative strengths of the two signals, their phase difference, and the design of the receiver.

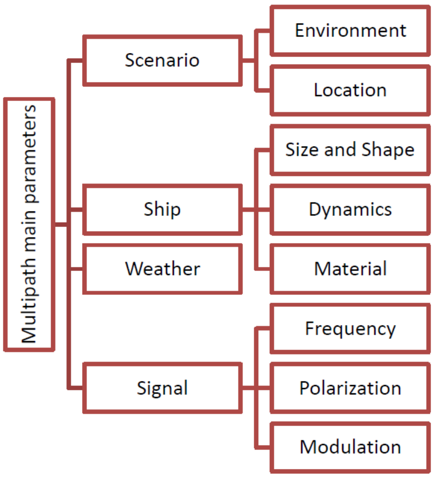


Figure 3-17. Main parameters that affect multipath magnitude

In the maritime domain, a greater multipath effect is expected compared to other segments like aviation. The aviation multipath model considers the hypothesis of a clear environment while in-flight, however, while in approach there are additional reflective surfaces that may contribute to multipath. The multipath effect in the maritime domain is caused by a combination of reflections from the sea surface and vessels, port cranes, bridges or other facilities. As such signal reflections can take place more frequently compared to the aviation domain, therefore the multipath error model shall be more restrictive than the one used in aviation and in some extreme cases (as IWW) equivalent to the models used in an urban environment.

3.4.3.2 NLOS

Non-Line of Sight (NLOS) Reception occurs when the direct LOS signal is obstructed (completely shadowed) and the user receiver only receives reflected signals. In this case, the pseudorange measurement error would be equal to the path delay, the difference between the length of the path taken by the reflected signal and the obstructed direct path between satellite and user. The power of NLOS signals varies greatly from the signals too weak to be tracked by some receivers to signals as strong as the ones directly received from the satellite, depending on the scenario and the surrounding environment generating this effect. High sensitivity receivers, however, can track very weak GNSS signals at the cost of being more prone to the acquisition and tracking of NLOS signals. The NLOS error affects both phase and code measurements and, although its value is typically around tens of meters, its theoretical maximum value is unlimited.

NLOS reception and multipath interference sometimes occur together. The most obvious case is where the direct signal from a particular satellite is blocked, and multiple reflected signals are received. In this case, the combined ranging error may be thought of as the sum of an NLOS error due to the strongest reflected signal and a multipath error due to the additional reflected signals interfering with the strongest signal.

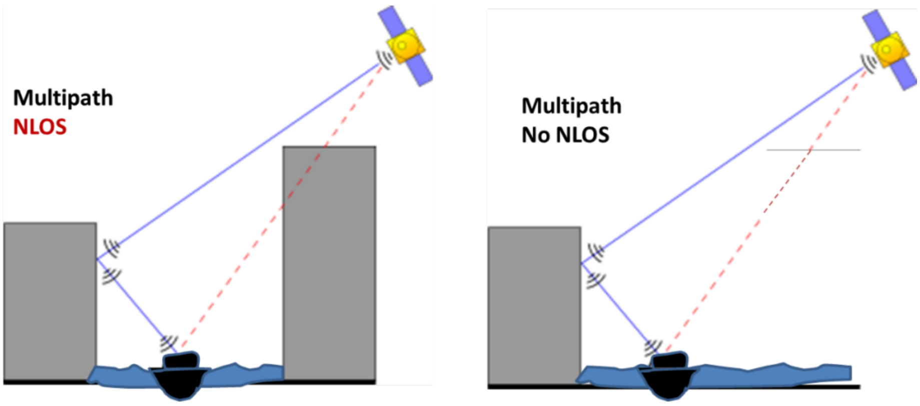


Figure 3-18: Multipath NLOS, maritime case

However, another scenario is where the direct signal is attenuated or diffracted such that it is weaker than a reflected signal. In this case, the receiver will typically track the reflected signal, resulting in an NLOS error, which will then be subject to multipath interference from the direct signal.

This NLOS effect could appear on specific maritime operations, for example, ports and inland waterways in urban environments. Though the term “multipath” is often used to describe NLOS reception, the two effects have different characteristics and need to be addressed separately as they can require different mitigation approaches [RD.35].

3.5 Prospective INSPIRe User-Integrity Concepts

3.5.1 Review of MarRINav M-RAIM Approach

The MarRINav project was a precursor to INSPIRe and may of the outputs from that project provide a good starting point for INSPIRe investigations. One thing that was investigated in MarRINav was a modified, maritime specific A-RAIM approach for integrity – referred to here as MarRINav M-RAIM.

MarRINav M-RAIM was adapted for maritime by GRAD from aviation's Advanced RAIM (ARAIM) and is based on a multiple hypothesis solution separation algorithm (MHSS), It is designed to be used in conjunction with SBAS augmentation to provide a HPL. M-RAIM has been developed to preserve maritime integrity and continuity performance requirements" [RD.38].

MarRINav M-RAIM operates on the principle that if a set of measurements are found to be faulty and can acquire an amount of error, conversely the navigation solution can be in error. However, the navigation solution will be accurate if the faulty measurement is excluded from the computations. To facilitate this principal detection thresholds and protection levels must be set [RD.38] defines these as follows:

"A detection threshold is set – this is the region around the all-in-view solution which must contain all of the subset solutions to avert an integrity alarm."

"A protection level is also set – this is the region around all of the subsets which is expected to also contain the true position of the receiver. If the protection level exceeds the HAL then the solution cannot be used."

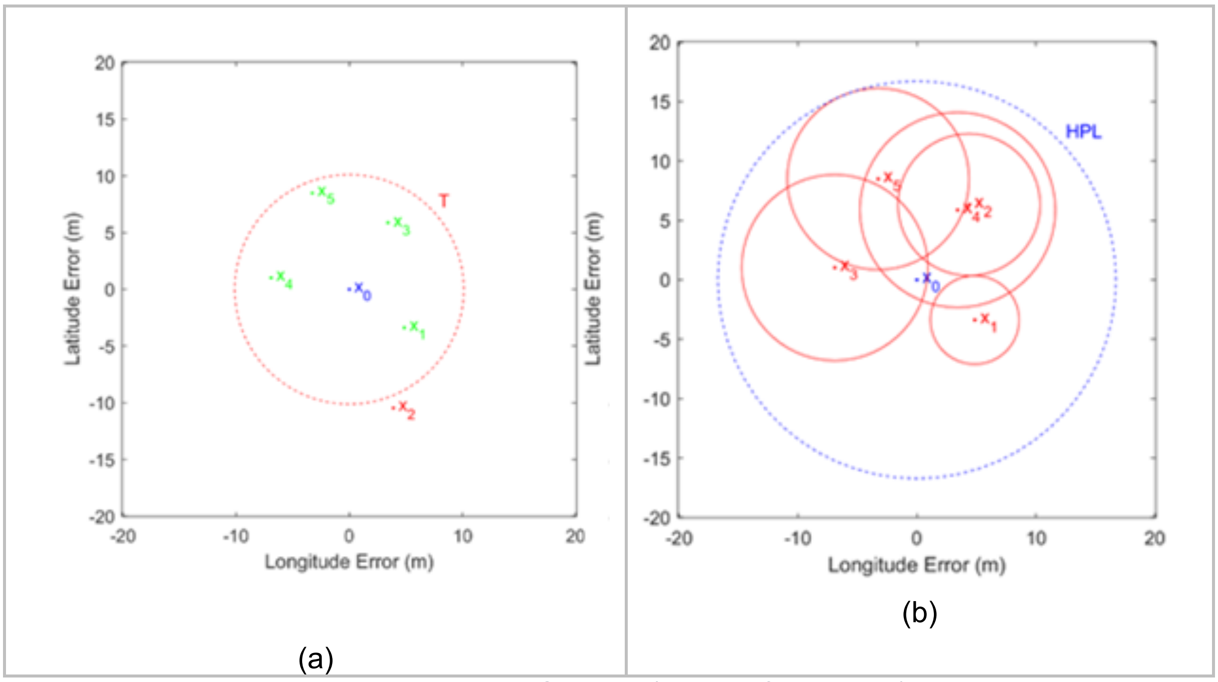


Figure 3-19 M-RAIM Operation (extracted from [RD.38])

Figure 3-19 shows the operation of the M-RAIM algorithm. Figure 3-19(a) shows the all-in-view solution (x_0) is compared to subset solution ($x_{1,3,4,5}$). Any of these solutions that falls outside of the Threshold (T) are considered erroneous for example x_2, and subsequently initiate an alarm. Figure 3-19(b), shows he HPL is then the union of all the subset solutions and their respective integrity bounds. If any of the subset solutions exceed the threshold under nominal measurement conditions or when no underlying faults exist, then this is a *false alarm* [RD.15]. The threshold value will determine the detection capability of the M-RAIM operation, hence setting the detection threshold too rigid causes too many false alarms and this harms the continuity performance of the system. Conversely, if setting the threshold is too lenient then faults might happen and not be detected, such a *missed detection* may cause the true position to lie outside the protection level.

Both MarRINav M-RAIM and ARAIM form many solutions from different subsets of GNSS measurements and can detect and mitigate a wide variety of different faults, including situations where multiple faults or failings happen simultaneously. The cost of this is the processing burden on the receiver. This is so to guarantee the solution is robust to any combination of several faulted measurements requires enumerating all possible combinations of these failures and computing subset solutions for each. Even allowing for many ignored, or un-monitored, fault modes this potentially requires a receiver to compute hundreds of solutions per epoch. The process is also quite dependent on *a-priori* estimates of the fault-free error distribution on each observation, and the *fault probability*, or risk that an observation drawn at random is from a "faulted" distribution, not conservatively bounded by the fault-free error model.

As documented in [RD.38] the biggest limitation of this process are the dependency on a-priori assumptions (both nominal fault-free error models and fault-probability values). These assumptions must be conservative for integrity to be guaranteed, and the magnitude of the HPL is critically dependent on them. If these assumptions are too conservative, then the HPL may be inflated too far, and the availability of the method may be damaged. If many potential simultaneous faults are considered, then the number of combinations of different kinds of faults can be extremely high resulting in significant computational cost in the receiver.

The MarRINav D3b GNSS Integrity Maritime Integrity at User Level with EGNOS-v3.0 and M-RAIM v2.0 document fully details the MarRINav M-RAIM technical principles and mathematical descriptions.

[RD.39] has highlighted some issues with the MRAIM algorithm and identified some advantage of the MRAIM system over the translation of the A-RAIM algorithm to the maritime domain, these are summarised in Table 3-8.

Table 3-8. Advantages and Disadvantages of MRAIM

Advantages	▪ Entire Integrity Risk to be allocated to the HPL since the vertical error and the VPL are not considered in the computations
	▪ Use of the Rayleigh over bounding distribution simplifies some of the mathematical calculations.
Disadvantages	▪ The algorithm is computationally demanding due to the calculation of large quantities of subset solutions, this is dependent on the number of simultaneous faults and the number of satellites in solution. As the number of usable GNSS constellations increases, this may become a serious burden on the processor.
	▪ The process is critically dependent on a-priori assumptions, both of the nominal fault free error models, and the assumed fault probabilities. Both of these should ideally be conservative descriptions of the real-world errors and risks involved.
	▪ Evaluating the fault probabilities will depend on very long-term data collection and the choice of fault-free error models
	▪ The process for determining the cut-off for allocating monitored and un-monitored faults is not yet determined.
	▪ For the MRAIM operation to be compatible with existing or future augmentation systems, the data produced by these systems (particularly the error bounds, such as UDRE) must be given as fault-free estimates, appropriate to a given fault probability.

3.5.2 Immediate and Long Term needs for Maritime Integrity

As seen in section 3.3.6 and 3.4, there are various gaps and ambiguities in the current definitions of integrity in the maritime domain. In the current situation where the mariner makes the final decision on navigation, looking at information from multiple sensors, charts and also visual aids, then not having defined failure probability allocation and integrity risk is less of an issue. However, in future operations with autonomous vessels, for example, the situation will be different and integrity will become important as the dependency on the navigation system increases, and liability for failures will have to be allocated to different sensors and systems rather than resting with the mariner.

The following table summarises the current situation and expected future needs in terms of safety or integrity.

Table 3-9. Comparison between current and expected user integrity needs

	Current Maritime integrity	Long-term Maritime integrity needs
Integrity definition	Ability to provide users with warnings within a specified time when the system should not be used for navigation	Ability to provide users with warnings within a specified time when the system is out of defined performance thresholds
Integrity concept	Checks to raise alarms out of nominal performances. Aid to Navigation for pilots	Combination of checks to raise alarms out of nominal performances and real time monitoring of current performances. Derived from safety risk of collision
Requirements	Incomplete integrity requirements available and ambiguous parameters proposed in IEC as example	Full set of requirements needed, to define performance thresholds, risk, and time to alert. This should be in combination with analysis of faults and failures to assess which faults and failures (and combinations) need to be considered
Validation procedures	IEC tests are vague. A receiver could pass the test without actually providing ambiguous safety not compared against any requirement	Unambiguous tests with defined configuration parameters and threshold
Liabilities	Pilot is liable for the navigation in almost every condition	Liability scheme has to be defined for Safety of Life services when there is no pilot
Technical	No technical analysis required to provide integrity	Required a safety analysis, environmental characterisation and hybridisation schemes

From this table it can be seen that there in many aspects there is a big gap between the current situation and what is required in the future to enable new operations such as autonomous vessels. Having such a big gap means that:

1. There is a significant amount of work to do (to investigate and define risk, to understand faults and probabilities, to characterise the maritime multipath environment, etc.) that will take several years to resolve
2. The jump from the current situation to a future scenario may be too big and imply procedures that are too different from what the mariner is used too

For these reasons, the focus of the integrity approach within INSPIRe should be to focus on a step-wise approach to start to bring us from the current maritime situation towards the long-term goal. Focusing on the most critical gaps that bring immediate benefit and do not impose procedures or usage that is too different to what the mariner is used to will bring immediate benefit whilst still moving along the path to the long-term ideal. From that initial algorithm, designed according to current status, sequential evolutions can then be proposed in later work packages to pave the way for the future integrity needs.

3.5.3 Proposed INSPIRe Maritime Integrity Approach

3.5.3.1 Introduction

From the current situation and summarised in the previous section, the most pressing gaps in maritime integrity are:

- How to check and decide if a navigation solution is 'suitable for navigation'
- A robust fault detection process
- Defined integrity tests and pass/fail criteria for receivers

These three aspects would bring immediate benefit and do not necessarily rely on longer term activities such as integrity risk analysis for different operations. They are also applicable to both GPS L1 only and GPS + EGNOS solutions.

The navigation solution checks and fault detection process are proposed and described below. The test definition are the subject of WP1 activities, and the scenarios will be used to test the algorithms and the results presented in section 5.

3.5.3.2 Maritime Integrity Process

Due to the issues aforementioned, INSPIRe propose an adaptation of the classical RAIM algorithm for fault detection, to comply with the maritime understanding of integrity and with the requirements set by IMO. Some additional checks on the solution geometry are used to decide if the solution is suitable for navigation.

As an overview:

- A snapshot weighted least squares navigation solution is computed on each epoch as normal. This may be GPS only or use SBAS corrections and integrity information where applicable
- An availability check is then performed to check if the solution is suitable for navigation
- If the solution is suitable, a fault detection process then checks if there are faults contaminating the position solution.
- If there are no faults, a geometry screening process is then performed to check if it would be possible to detect faults in the current solution that would impact the suitability of the navigation solution
- Depending on the results of the checks, a simple status flag is output (red/amber/green), in line with what the mariner is currently familiar with

These parts are described in more detail below.

3.5.3.2.1 Navigation Solution

In the first step, an all-in-view, weighted least squares solution is made, using the pseudorange measurements, and solved by local linearization and iteration.

In the GPS L1 case, all satellites above the elevation mask and with healthy status in the broadcast navigation message are used.

In the GPS + EGNOS case, differential corrections are applied (fast/slow and ionosphere) and satellites are only used if they are above the elevation mask, with healthy status in the broadcast navigation, and do not have 'do not use' status in the broadcast SBAS messages.

Satellite weighting is informed by a simple error estimation process, comprising broadcast error figures (URA, UDRE, depending on augmentation) and simple models for the local receiver noise and environment.

The outcome of this is a standard position solution for the current epoch.

3.5.3.2.2 Availability Check

The next stage is a simple check on the derived solution to determine whether it is "suitable for navigation" as defined by the maritime GPS receiver specifications [RD.41]. The solution must (at minimum) have:

- Not less than five satellites in solution, as RAIM must be enabled for use always
- HDOP not more than four
- GDOP not more than six
- Estimated 95% Horizontal Accuracy not more than the applicable threshold (e.g.10m for coastal or 100m for Open Ocean)

If any of these simple checks are failed then the solution is deemed not to be suitable for navigation and the "red light" integrity alarm is raised to warn the mariner not to use the system. If these checks are passed, a fault-detection (FD) process follows.

In the fault detection part, the RAIM test statistic is formed – as a baseline this is the weighted sum square residuals as defined in section 3.2.3.2.1. This is a Chi-Squared hypothesis test of the validity of the assumed error models. The test statistic is compared to a pre-computed detection threshold, which depends on the number of degrees of freedom of the solution (the number of satellites in solution minus the number of co-ordinate parameters solved-for).

These thresholds are pre-computed to provide a controlled risk of false alarm, per independent sample, of 10^{-5} (this risk is an INSPIRE assumption, proposed in MarRINav). This is to ensure that the continuity requirement 99.97% per 15 minutes can be met by the system.

If the test statistic exceeds the detection threshold, then the "red light" integrity alarm is raised to warn the mariner not to use the system.

Note that in the future, Fault Detection and Exclusion (FDE) may be used as a refinement of this process, and may be a user-set option. For the purposes of implementation and testing within INSPIRE, FDE will not be enabled.

If the integrity alarm is not sounded (the test statistic lies below threshold) then the Screening process is enacted.

3.5.3.2.3 Geometry Screening

This is an INSPIRe proposal to add to the existing maritime requirements. The purpose of this part is to determine in a simple way if the geometry of the solution is good enough such that any applicable faults that may affect the system can be detected.

The way this is proposed to be done is for each potentially faulty element of the navigation solution (nominally per individual satellite for the GPS only case), a subset solution is formed by eliminating the faulty element from the all-in-view solution.

Then, for each of these subset solutions, the “suitable for navigation” tests are applied. Each subset must have:

- HDOP not more than four
- GDOP not more than six
- Estimated 95% Horizontal Accuracy not more than the threshold (e.g. 10m for coastal or 100m for Open Ocean)
- Not less than *four* satellites in solution, as RAIM is not applied to these subsets.

If *any* of these tests fail, for *any* of the subset solutions, then it cannot be sure that the solution geometry is good enough to detect faulty measurements and so the “green light” cannot be shown and must be replaced by an “amber light” warning.

If all of these tests pass, for all of the subset solutions, then the “green light” integrity guarantee can be shown to the mariner.

3.6 Conclusion

This review has taken a look at the existing integrity the aviation domain vs that of maritime domain. The study reviewed the requirement set out by the governing bodies of both sectors, and it has been observed that both sectors definition of integrity are in alignment, however the requirements guiding the performance standards of these sectors are quite different.

Aviation performance standards provides well defined concepts, procedures, allocation and understanding of failure risk. The main reason of this stringent and extensive regulation is because several key processes for the flight safety take the navigation information as inputs and the risk of accident is required to be allocated in a top-down approach. While the maritime performance standards are vague and mostly tailored after the aviation standards.

Civil aviation has traditionally been the driver for the development of the GNSS integrity concept. However, it is important to highlight as concluded in previous sections the concept of integrity is different for the Maritime community. Therefore, the aviation safety approach cannot be directly used in the maritime sector, partly due to its rigidity and computational complexity. INSPIRe as a project will undertake the ground work to deliver a maritime user level integrity solution, through the assessment, production and validation suitable algorithms for user-level integrity for PNT solutions.

4 HIGH LEVEL ALGORITHM DESIGN

This section provides a high-level design for the GPS single frequency integrity algorithms.

4.1 Mathematical Description

4.1.1 Navigation Solution

We consider the mathematical process of deriving a position fix (x) from a set of pseudo-range measurements (y). Each measurement (y_k) equals the range to the k^{th} satellite (ρ_k), plus a common receiver clock-offset (τ), plus some measurement noise (ϵ_k):

$$y_k = \rho_k + \tau + \epsilon_k$$

The process is *non-linear*, since the range (ρ) to each satellite depends on the position of the user in a non-linear way:

$$\rho = \|x_{sat} - x\| = \sqrt{(X_{sat} - X_{user})^2 + (Y_{sat} - Y_{user})^2 + (Z_{sat} - Z_{user})^2}$$

The solution is to guess the user's Approximate Position (x_{AP}) and determine the pseudo-range measurements that *would have been made* from that location (y_{AP}). The difference between the actual measurements (y_{obs}) and those expected from the AP are then used to solve for an update to the AP *as if the process were linear*: We assume a small change in pseudo-ranges (dy) results from some linear function of the change in position (dx).

This linear function is the *Jacobian*, or derivative matrix, which is referred to as the *geometry* matrix and use the letter (G). This is re-calculated for each update, as it depends on the AP:

$$G = \left.\frac{\partial y}{\partial x}\right|_{AP}$$

$$dy = Gdx$$

This can be written analytically in ENU reference frame in terms of the elevation (θ) and azimuth (ϕ) of each satellite from the AP.

$$G = \begin{bmatrix} \cos(\theta_1)\sin(\phi_1) & \cos(\theta_1)\cos(\phi_1) & \sin(\theta_1) & 1 \\ \cos(\theta_2)\sin(\phi_2) & \cos(\theta_2)\cos(\phi_2) & \sin(\theta_2) & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \cos(\theta_n)\sin(\phi_n) & \cos(\theta_n)\cos(\phi_n) & \sin(\theta_n) & 1 \end{bmatrix}$$

Here n is the number of satellites used in solution and the matrix is provided for only one constellation.

The last column is for the time co-ordinate and should be the speed of light (c). This can be artificially set to one (to solve the clock offset equivalence in meters) for better numerical scaling of the matrix.

A weighting matrix is calculated from models of the estimated (fault-free) variance of each pseudo-range measurement:

$$W = \begin{bmatrix} \sigma_1^{-2} & 0 & \cdots & 0 \\ 0 & \sigma_2^{-2} & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \sigma_n^{-2} \end{bmatrix}$$

These models can be drawn from the extant literature, or existing receiver MOPS. Appendix A goes into more detail, for example, the following model might be chosen:

$$\sigma^2 = \sigma_{URA}^2 + \sigma_{Noise}^2 + \sigma_{M-path}^2 + \sigma_{Tropo}^2 + \sigma_{Iono}^2$$

The least squares update to the solution can be derived, but is given as a standard result by the following:

$$(x_{new} - x_{AP}) = (G^T W G)^{-1} G^T W (y_{obs} - y_{AP})$$

The AP is updated iteratively until convergence: changes in the position $(x_{new} - x_{AP})$ are suitably small (e.g., <1mm) that further updates are unnecessary.

Once convergence is found, it is often simpler to re-define the origin of the co-ordinate system as the (unknown) true position of the receiver, and the origin of the measurement space is a set of idealised “perfect” pseudo-range measurements that correspond to this “true” position:

$$y = y_{obs} - y_{true}$$

$$\hat{x} = x_{LS} - x_{true}$$

By defining the projection matrix:

$$K = (G^T W G)^{-1} G^T W$$

We write the simpler equation:

$$\hat{x} = Ky$$

The estimated co-variance of the co-ordinate error can then be found in terms of the assumed weighting (W), taking this to be a good approximation of the expected co-variance of the observations ($W \cong C_y$). The Dirac notation $\langle \quad \rangle$ is used to indicate the expectation operator.

$$C_{\hat{x}} = \langle \hat{x}^2 \rangle = \langle \hat{x} | \hat{x}^T \rangle = \langle Ky | y^T K^T \rangle$$

$$= (G^T W G)^{-1} G^T W \langle y | y^T \rangle W G (G^T W G)^{-1}$$

$$= (G^T W G)^{-1} G^T W C_y W G (G^T W G)^{-1}$$

$$\cong (G^T W G)^{-1} G^T W W^{-1} W G (G^T W G)^{-1}$$

$$C_{\hat{x}} = (G^T W G)^{-1}$$

This co-variance estimate can then be used to estimate the 95% accuracy of the resulting solution:

$$A_{95} \cong 1.73 DRMS = 1.73 \sqrt{\sigma_{lat}^2 + \sigma_{lon}^2} = 1.73 \sqrt{C_{\hat{x}}^{(1,1)} + C_{\hat{x}}^{(2,2)}}$$

We use the bracketed superscript notation to indicate the numbered cell in the matrix. A less optimistic estimate (especially in case of high DOP) can be found using the elliptical formula:

$$A_{95} \cong 2.45 \sqrt{\frac{1}{2}\left(C_{\hat{x}}^{(1,1)} + C_{\hat{x}}^{(2,2)} + \sqrt{\left(C_{\hat{x}}^{(1,1)} - C_{\hat{x}}^{(2,2)} \right)^2 + 4 C_{\hat{x}}^{(1,2)}} \right)}$$

The DOP matrix (D) can be found:

$$D = (G^T G)^{-1}$$

This can then yield values for the horizontal and geometric dilution of precision (DOP):

$$HDOP = \sqrt{D^{(1,1)} + D^{(2,2)}}$$

$$GDOP = \sqrt{D^{(1,1)} + D^{(2,2)} + D^{(3,3)}}$$

Following the previous notation above is defined:

$$\hat{y} = G\hat{x}$$

The residuals are then:

$$\omega = y - \hat{y} = y - GKy = (I_n - GK)y$$

$$\omega = Ay$$

This defines the parity-space projection matrix (A).

4.1.2 Availability Check

The availability check function consists in a simple set of checks applied to the derived solution to determine whether it is "suitable for navigation" as defined by the maritime GPS receiver specifications. The solution must (at minimum) have:

- HDOP ≤ 4
- GDOP ≤ 6
- Estimated 95% Horizontal Accuracy ≤
  - 10m for Coastal, Harbour and Port approach Navigation
  - 100m for Open Ocean Navigation
- Available satellites ≥ 5, as RAIM must be enabled for use always.

The DOP checks are implemented largely for backwards compatibility with the existing receiver specifications and testing processes.

If any of these simple checks are failed, then the "red light" integrity alarm is raised to warn the mariner not to use the system. If these checks are passed, a fault-detection (FD) process follows

4.1.3 Fault Detection test

4.1.3.1 Overview

If the availability checks are passed, a fault-detection (FD) process follows.

The pseudo-range residuals are calculated, and a weighted sum square defines the test statistic. This is a Chi-Squared hypothesis test of the validity of the assumed error models. The test statistic is compared to a pre-computed detection threshold, which depends on the number of degrees of freedom of the solution (the number of satellites in solution minus the number of coordinate parameters solved-for).

These thresholds are pre-computed to provide a controlled risk of false alarm, per independent sample, of 10^{-5}. This is to ensure that the continuity requirement 99.97% per 15 minutes can be met by the system[7].

If the test statistic exceeds the detection threshold, then the "red light" integrity alarm is raised to warn the mariner not to use the system.

Fault Detection and Exclusion (FDE) may be used by some future refinement of this process and may be a user-set option.

If the integrity alarm is not sounded (the test statistic lies below threshold) then the Screening process is enacted.

4.1.3.2 Processing

If previous availability checks pass, the solution residuals are calculated as the difference between the pseudorange measurements that would be expected from the co-ordinate solution, and those that are actually measured. A weighted sum of residuals is calculated:

[7] This False Alarm probability is an INSPIRE assumption, proposed in MarRINav

$$t^2 = \omega^T W \omega = y^T (I_n - GK)^T W (I_n - GK) y = y^T M y$$

This is then compared to a detection threshold (T^2) defined by integrating the tail of the chi-squared distribution with n-4 degrees of freedom up to the percentile defined by a pre-allocated risk of false-alarm. In our case this risk is suggested to be 10^{-5}, yielding the following table of pre-computed thresholds:

Table 4-1 – Fault Detection threshold as a function of n, the number of satellites used in the navigation solution

Number of Satellites (n)	Threshold (T)
4	N/A (0)
5	4.42
6	4.80
7	5.09
8	5.34
9	5.55
10	5.75
11	5.94
12	6.11
13	6.27
14	6.43
15	6.57
16	6.71
…	etc.

If the test-statistic exceeds the detection threshold ($t^2 > T^2$) then this is the condition for the RAIM algorithm to raise the "red light" integrity warning. The navigation solution is not shown to the mariner, and the process stops here until the next epoch.

If $(t^2 > T^2)$ raise a red integrity flag, if no FE available

This red light will be kept until a safer status is kept for a certain duration (e.g. 6 seconds)

If the test-statistic lies below the detection threshold ($t^2 \leq T^2$) then perform the geometry screening process.

4.1.4 Geometry Screening

A "fault" is defined as when one particular element of the position-fixing process has failed and any assumptions that use this element can no longer be trusted. For example, a loss of clock synchronisation (e.g., a clock failure) on a satellite will cause its time-base to ramp away from GPS system time and the broadcast URA (or corrected UDRE) is no longer valid.

To detect a fault, the RAIM algorithm uses the chi-squared test, as described above. To measure the *capability of the RAIM algorithm to do this detection*, a subset solution is formed that excludes the data feared to be incorrect. To continue the example above, to measure the ability to detect the satellite clock failure, a subset solution is formed by removing this feared faulty satellite from solution.

If the subset solution is then also "suitable for navigation" as described in [RD.4] then this is indicative that RAIM will have adequate geometric detection fidelity to flag this fault before it becomes excessively large. Any likely fault for which adequate detection fidelity is not guaranteed is grounds for raising the "amber light" caution.

For the solution to be shown a "green light" guarantee, all subsets corresponding to likely fault conditions must pass all the following:

- HDOP < 4
- GDOP < 6
- Horizontal Accuracy (95%) < threshold (e.g. 10m for coastal or 100m for Open Ocean)
- number of satellites > 4

We note that this is an arbitrary decision threshold and holds no bearing upon an agreed level of integrity performance, or error bounding. However, it does agree with the wording in the extant maritime receiver performance standards [RD.4]. A method of screening geometries to eliminate unsafe solutions (for which a substantial fault may exist un-detected) is necessary for the safety of the "green light" guarantee passed to the mariner.

Subset DOP matrices (D_i) and co-variance matrices ($C_{x\,i}$) can be determined from the all-in-view matrices (D and C_x) without an excessive computational burden by applying the rank-one update formula.

4.1.5 Summary

Following this process, the following output states may be applicable.

Table 4-2: Summary of Maritime integrity algorithm output states

Availability Check	Fault Detection	Geometry Screening	Status Flag
FAIL	NA	NA	RED
PASS	FAIL	NA	RED
PASS	PASS	FAIL (any subset)	AMBER
PASS	PASS	PASS	GREEN

5 DESCRIPTION OF ALGORITHM TESTING

This section presents an overview of the experimentation plan for the evaluation of the algorithm and a summary of the results of algorithm testing. The sections that follow then go into more detail on each element. The purpose of the experimentation is to assess the MGRAIM algorithm developed.

The experimentation consists of the following sequential stages:

- Data collection & generation
- Data processing
- Performance evaluation

These stages are discussed in the following subsections.

5.1 Data Generation and Data Processing

The functional testing and performance evaluation was executed based on the collection of real GNSS data (GPS and Galileo observables), using GMV facilities, in Nottingham.

5.1.1 GNSS Data

GNSS Data are measured with the Septentrio PolarRx5S. The PolaRx5S from Septentrio is a high-performance GNSS receiver capable of multi-constellation position solutions and logging, at a maximum of 100Hz. Supported constellations include GPS L1, L2, L5, Galileo E1, E5 (a, b, AltBoc) E6, BeiDou, B1, B, B3 and SBAS (Including EGNOS).

The PolaRx5S is currently located at the GMV offices in Nottingham as part of a receiver testbench in the lab. The receiver uses a single NAVX 3G+C antenna, which collects Static datasets from open sky, situated on the Sir Colin Campbell Building roof, which can receive all available GPS, Galileo, GLONASS, BeiDou and SBAS signals. Table 5-1 below provides a summary of the data collected for analysis.

Table 5-1 GPS Data collected for analysis

Date	Duration		Constellation/Frequency	File Format	Conversion Tool
	From	To			
2022/ 09 /28	10:15:00	11:00:16	GPS/ L1	RINEX	RTKCONV 2.4.3 (SBF to RINEX)

5.1.2 EGNOS Data

The EGNOS data used within this project was retrieved from GMV's internal archive, in the EMS format. The EMS format has been defined by ESA for the provision of EGNOS messages. EMS format 2.0 is described in [RD.48]. GMV has a tool which decodes the messages logged. The output of the decoding software is two *.csv files containing the following information:

- Fast and long-term correction file, for each epoch (1s rate) in the chosen time.
- Ionosphere grid information file for the chosen time period.

Table 5-2 EGNOS Data collected for analysis

Date	Duration		PRN	FILE NAME	File Format	Conversion Tool
	From	To				
2022/ 09 /28	10:00:00	11:00:00	123	h10/ h11	EMS	GMV EMS Decoder

5.1.3 Simulation Data Generation

Simulated data provides an option to cover scenarios that would otherwise not be possible using field data alone. [RD.5] provides the specification for the Threats and Faults which are applicable to and will be used to develop the INSPIRe integrity solutions. To facilitate the analysis of these faults on the positioning solution, GMV has created a series of functions to introduce the errors to the RINEX files.

Table 5-3 Fault Injection

Fault	Baseline Function	Notes
Satellite Clock failure (ramp)	The fault injection tool applies a ramp error on a specified satellite	Standard clock failure on a single satellite – determined to be a steady clock ramp on one measurement.
Satellite Clock failure (bias)	The fault injection tool applies a bias value to a single SV	Clock failure on a single satellite leading to a bias/offset.
Satellite Bad Ephemeris Upload	Modification of parameters in the navigation message	Single satellite failure due to a bad ephemeris upload results in incorrect information.
Elevated Ionospheric Delay (TEC)	The fault injection tool applies an elevated Ionospheric Delay (TEC)	Faults due to ionospheric disturbances.
Satellite multipath	The fault injection tool applies an elevation-dependent error is added to each pseudo range observation, with a random noise component included	Multi-path induced error on a single satellite e.g., the introduction of oscillating bias error. Typical of a maritime environmental hazard.

5.1.4 Data Processing

The collected data will be processed off-line and in non-real-time using the algorithm and several supporting tools. A set of algorithm performance test scenarios are defined in Section 5.2. The following high-level processing step shall be carried out:

- Run TPDF for each test scenario, configured according to test scenario definition.
  - Inputs:
    - RINEX observation file and navigation file
    - If SBAS legacy mode:
      - *.csv files output by EGNOS decoder for applicable calendar day.
  - Outputs:
    - PVT results files (.csv)
    - SBAS engine (Legacy)
    - MGAIM engine
  - Residual data files (.csv)

5.2 Test Scenarios

A set of 16 test scenarios has been defined, as described in the table below.

Table 5-4 Test Scenarios

Test Scenario	Correction mode	EGNOS mode	Fault injection	Smoothing time constant
TS.01	EGNOS disabled	N/A	None	100s
TS.02	EGNOS enabled	Legacy	None	100s
TS.03	EGNOS enabled	Legacy	Single Satellite Clock failure (ramp) - High Elevation SV	100s
TS.04	EGNOS disabled	N/A	Single Satellite Clock failure (ramp) - High Elevation SV	100s
TS.05	EGNOS enabled	Legacy	Single Satellite Clock failure (ramp) - Low Elevation SV	100s
TS.06	EGNOS disabled	N/A	Single Satellite Clock failure (ramp) - Low Elevation SV	100s
TS.07	EGNOS disabled	N/A	Single Satellite Clock failure (bias) - High Elevation SV	100s
TS.08	EGNOS enabled	Legacy	Single Satellite Clock failure (bias) - High Elevation SV	100s
TS.09	EGNOS disabled	N/A	Single Satellite Clock failure (bias) -Low Elevation SV	100s
TS.10	EGNOS enabled	Legacy	Single Satellite Clock failure (bias) -Low Elevation SV	100s
TS.11	EGNOS disabled	N/A	Single Satellite Bad Ephemeris Upload - High Elevation SV	100s
TS.12	EGNOS enabled	Legacy	Single Satellite Bad Ephemeris Upload - High Elevation SV	100s
TS.13	EGNOS disabled	N/A	Single Satellite Multipath error - High Elevation SV	100s
TS.14	EGNOS disabled	N/A	Single Satellite Multipath error Upload - Low Elevation SV	100s
TS.15	EGNOS disabled	Legacy	Single Satellite Ionospheric error - High Elevation SV	100s
TS.16	EGNOS enabled	Legacy	Single Satellite Ionospheric error - Low Elevation SV	100s

6 ASSESSMENT OF SUITABILITY OF ALGORITHM

This section will contain an assessment of the suitability of the algorithm and highlight any areas for further development and investigation.

The algorithm assessment was carried out using the algorithm design described in Section 4. Here we analyse the algorithms' ability to detect GNSS faults as described in Section 4.1.3 and to raise the appropriate alert as defined in Table 4-2 in Section 4.1.5. To detect a fault, the RAIM algorithm uses the chi-squared test. The test statistic is compared to a pre-computed detection threshold, which depends on the number of degrees of freedom of the solution (the number of satellites in solution minus the number of coordinate parameters solved-for). As mentioned previously these thresholds are pre-computed to provide a controlled risk of false alarm, per independent sample, of 10^{-5}. Therefore, if the test-statistic exceeds the detection threshold ($t^2 > T^2$) then this is the condition for the RAIM algorithm to raise the "red light" integrity warning. The pseudo-range error model used in the test statistic computation is described in Section 3.2.3.1.2.

It should be noted that for illustrative purposes for results where faults are injected, and the red integrity flag is raised the horizontal error is plotted to show the potential effect of the fault but position is not provided in such a case.

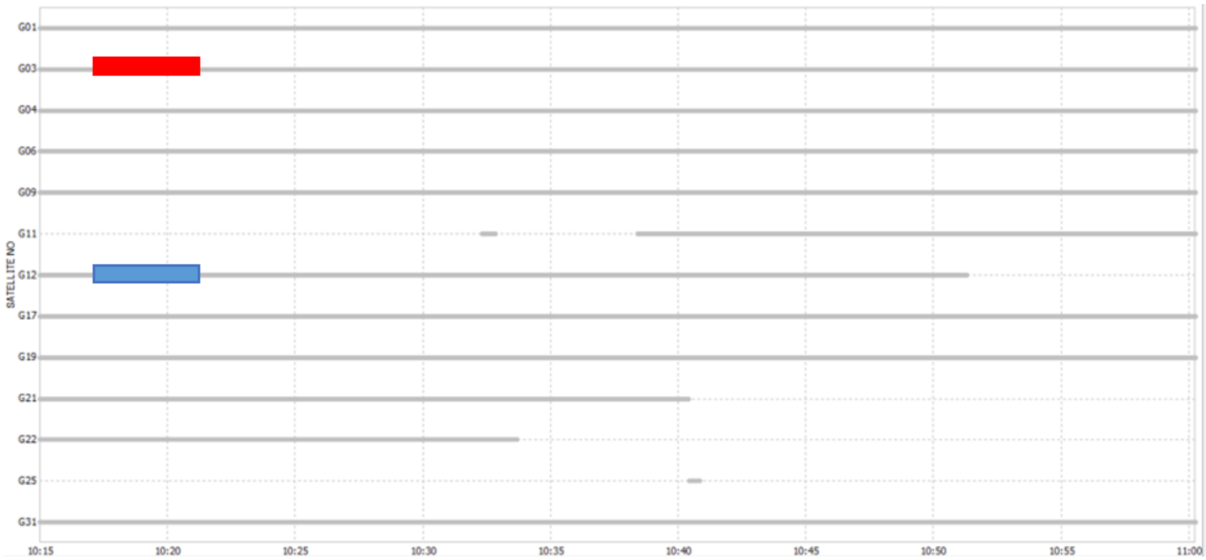


Figure 6-1 Satellite visibility condition and Fault injected on satellite G03 at time =110s to time = 410s

Figure 6-1 depicts the satellite visibility for the selected dataset and the red and blue windows highlight the satellite and the period in which the faults were been injected on the high satellites G03 with an elevation of 64° and azimuth of 74° and low elevation satellites G12 with an elevation of 7° and azimuth of 336° . For the satellites used the faults were injected at t=110s (SOW: 296228s) for a period of 300s to end at to t = 410s (SOW: 296528s). The results present here after are for single satellite fault case according to the test scenarios defined in Section 5.2.

6.1 Presentation of Experimentation and Evaluation results

6.1.1 Results of a Clean dataset

This subsection shows the results generated using a smoothing constant of 100 seconds based on the following test scenario:

Test Scenario	Correction mode	EGNOS mode	Fault injection
TS.01	EGNOS disabled	N/A	none
TS.02	EGNOS enabled	Legacy (GPS L1)	none

6.1.1.1 TS01 – PVTI Performance Analysis (EGNOS Disabled)

Figure 6-2 and Figure 6-2 show fault detection test results from Test Scenario 01 EGNOS disabled. Figure 6-2 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test as described in Section 4.1.3. It can be seen from the graph that the test statistic does not exceeds the detection threshold, when this occurs the “green light” integrity alarm/flag is raised, the average test statistic is 0.282 and the threshold is 5.94. Figure 6-2, shows integrity flags and the horizontal errors within the solution generated.

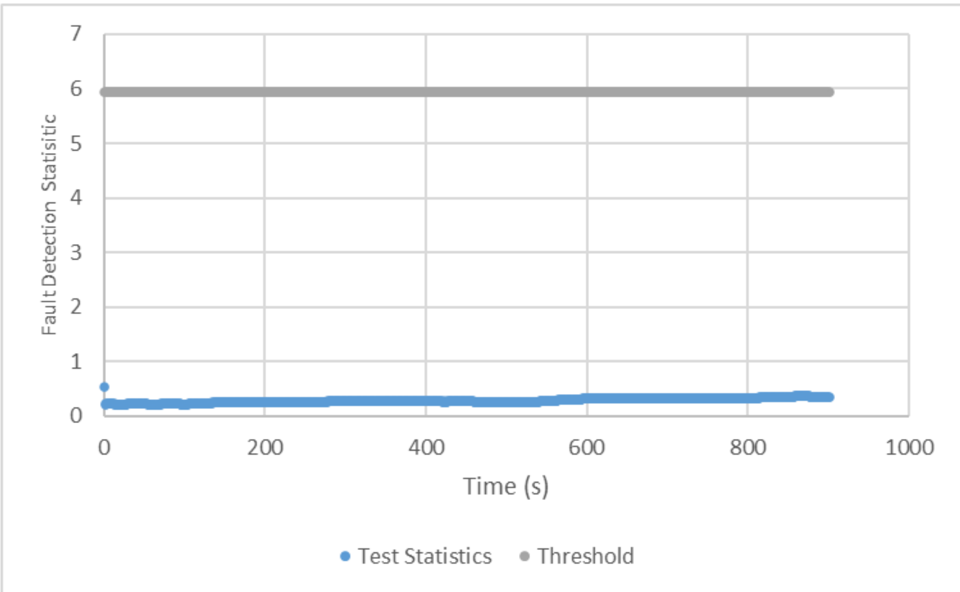


Figure 6-2 FD results from MRAIM in Ephemeris fault-free case

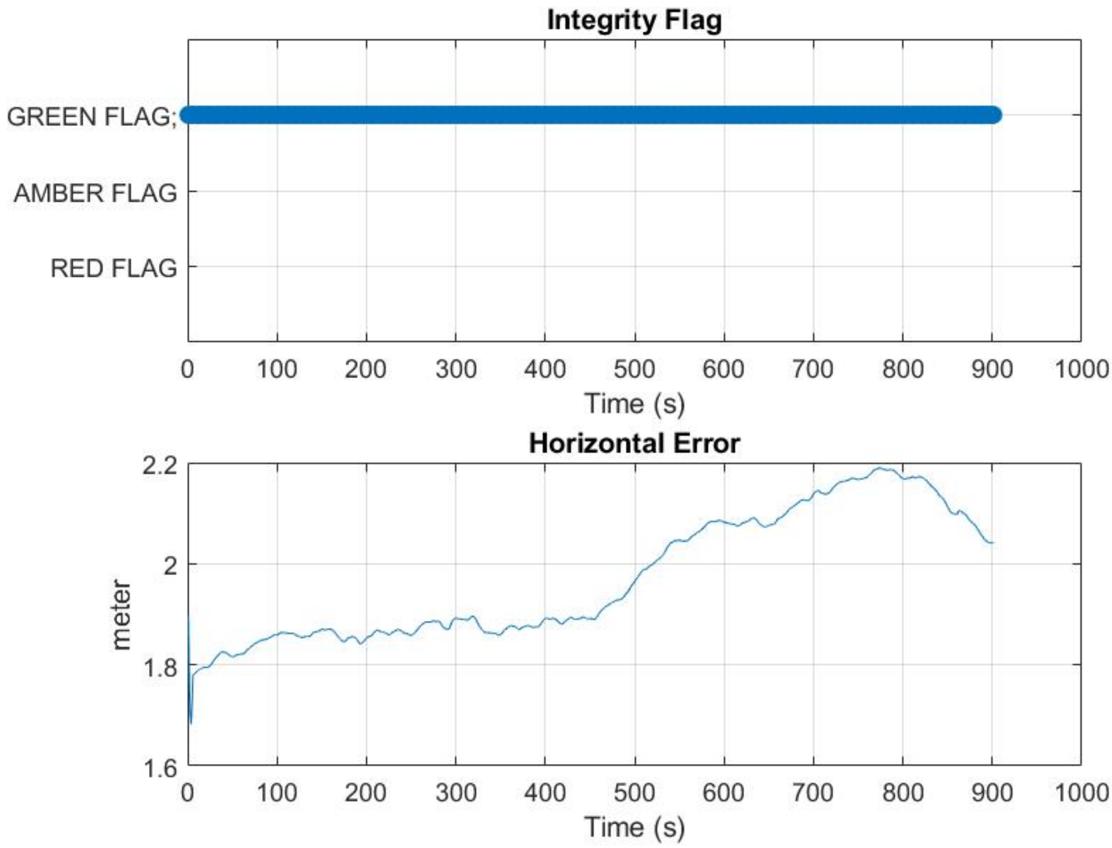


Figure 6-3 The MGRAIM Integrity Flag (above) and Horizontal Error

The solution performance is summarised in Table 6-1. For GPS L1 the horizontal error is 2.171m with a percentile of 95%.

Table 6-1 TS01 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-1.064	0.115	1.228
East	1.659	0.097	1.802
Up	-0.77	0.378	1.344
Horizontal	1.972	0.126	2.171

Figure 6-4 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

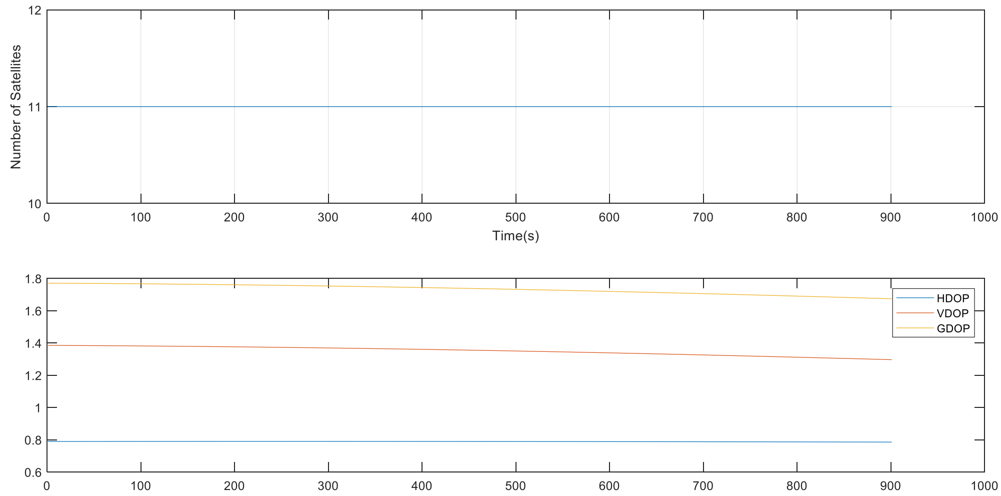


Figure 6-4 Number of SV used to generate the PVT solution and the DOP Values

6.1.1.2 TS02 – PVTI Performance Analysis (EGNOS Enabled)

Figure 6-5 and Figure 6-6 show fault detection test results from Test Scenario 02 EGNOS enabled. Figure 6-5 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test as described in Section 4.1.3. It can be seen from the graph that the test statistic does not exceeds the detection threshold, when this occurs the "green light" integrity alarm/flag is raised, the average test statistic is 1.188 and the threshold is 5.94. Figure 6-6, shows integrity flags and the horizontal errors within the solution generated.

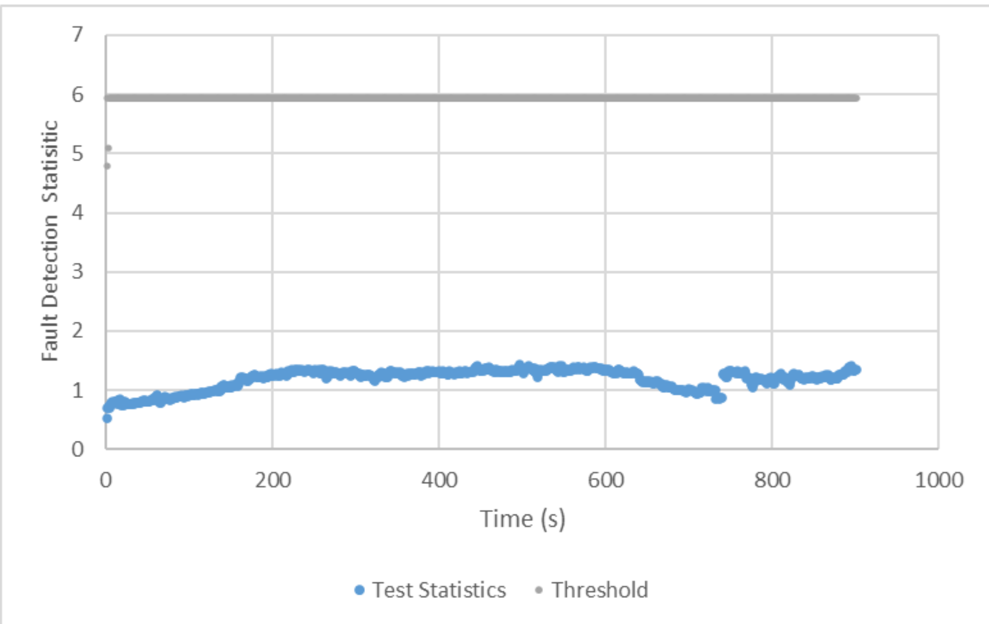


Figure 6-5 FD results from MRAIM in Ephemeris fault-free case

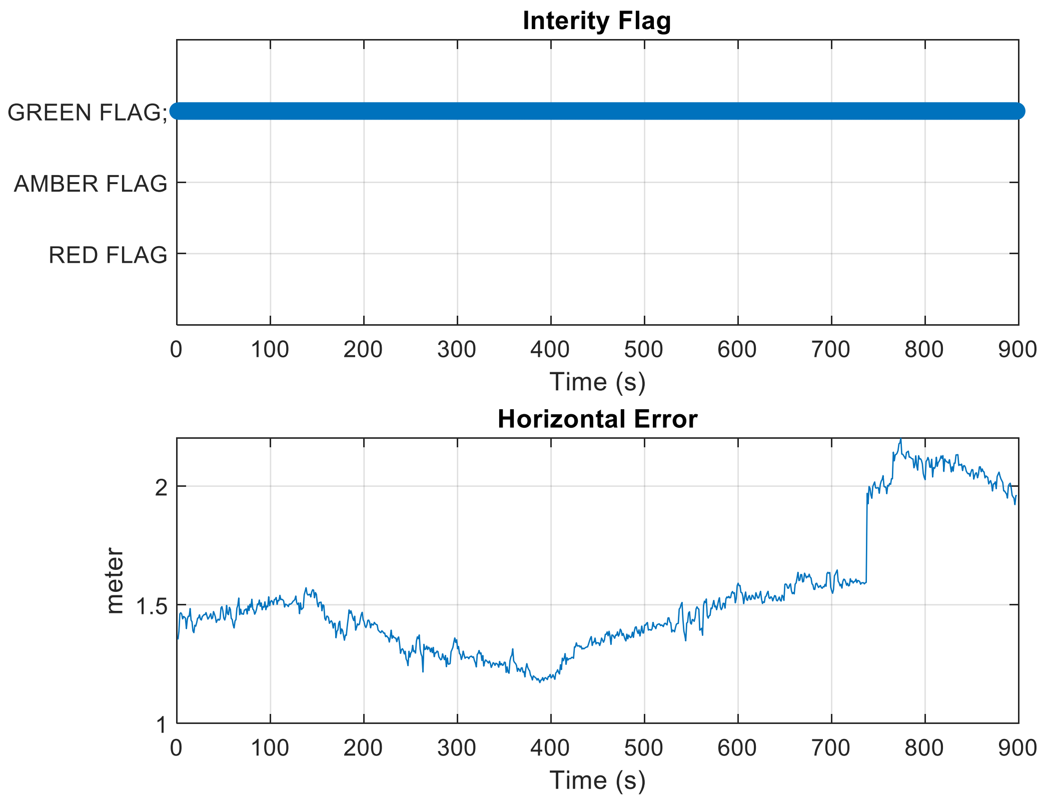


Figure 6-6 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-1. For GPS L1 the horizontal error is 2.101m with a percentile of 95%.

Table 6-2 TS02 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-0.482	0.223	0.889
East	1.443	0.247	1.899
Up	0.155	0.371	0.65
Horizontal	1.535	0.269	2.101

6.1.2 Evaluation of a ramp error on a single high-elevation SV

The ramp-type fault refers to the slowly varying cumulative error which might be resulted in a jump in frequency and drift in the phase of the satellite clock. This subsection shows the results generated using a smoothing constant of 100 seconds based on the following test scenario:

Test Scenario	Correction mode	EGNOS mode	Fault injection	Comment
TS.03	EGNOS enabled	Legacy (GPS L1)	Single Satellite Clock failure (ramp) - High Elevation SV	apply ramp error on a single high-elevation SV
TS.04	EGNOS disabled	N/A	Single Satellite Clock failure (ramp) - High Elevation SV	apply ramp error on a single high-elevation SV

Table 6-3 shows the configuration parameters and values used to create the ramp fault injection dataset. The ramp error at the speed of 0.4m/s is injected into the original pseudo-range of a single satellite from t=110s (SOW: 296228s) to t = 410s (SOW: 296528s).

Table 6-3 TS03/TS04 Configuration

Parameter	Value	Comment
Start time [GPS Week SOW]	[2229 296228];	represents the time and duration of the injection of the fault
End time [GPS Week SOW]	[2229 296528];	
Constellation	['G'];	The constellation on which is affected
PRN	[3];	Satellites in which the fault was injected
Range drift	[0.4m/s]	

6.1.2.1 TS03 – PVTI Performance Analysis (EGNOS Enabled)

Figure 6-7 and Figure 6-8 show fault detection test results from Test Scenario 03 EGNOS disabled. Figure 6-7 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the "red light" integrity alarm/flag is raised. Figure 6-8, shows integrity flags and the horizontal errors within the solution generated.

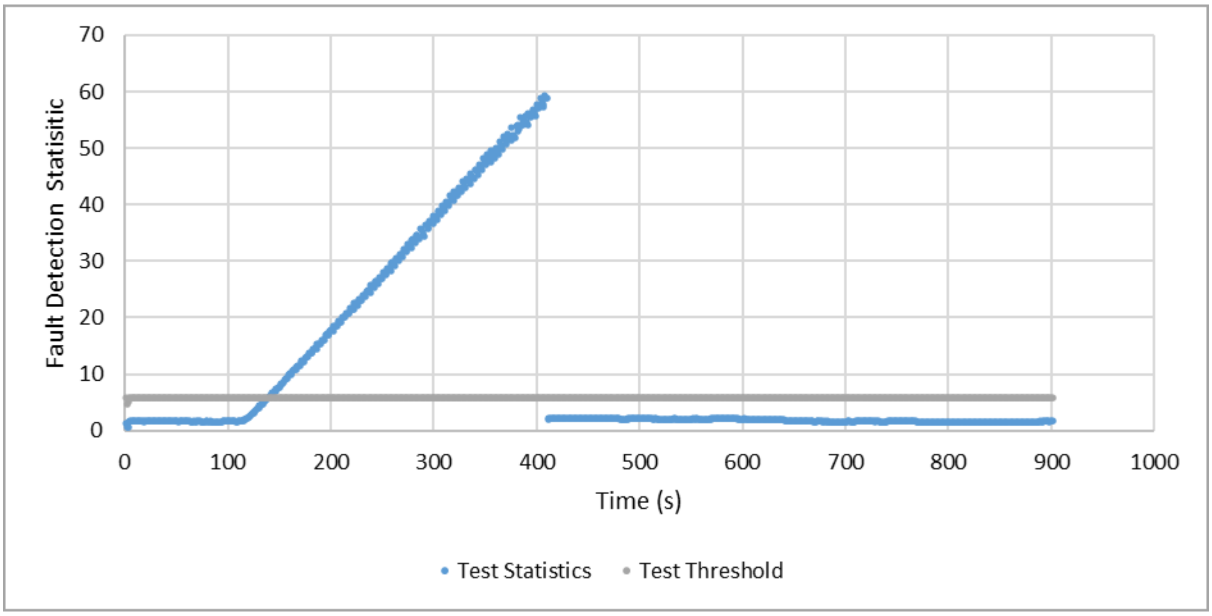


Figure 6-7 FD results from MGRAIM in ramp fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test-statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 162s where $t^2 = 6.04$ $T^2 = 5.94$ and ended at time 410s where $t^2 = 58.82$ $T^2 = 5.94$. The horizontal error values at these times were 4.55m and 44.09m respectively.

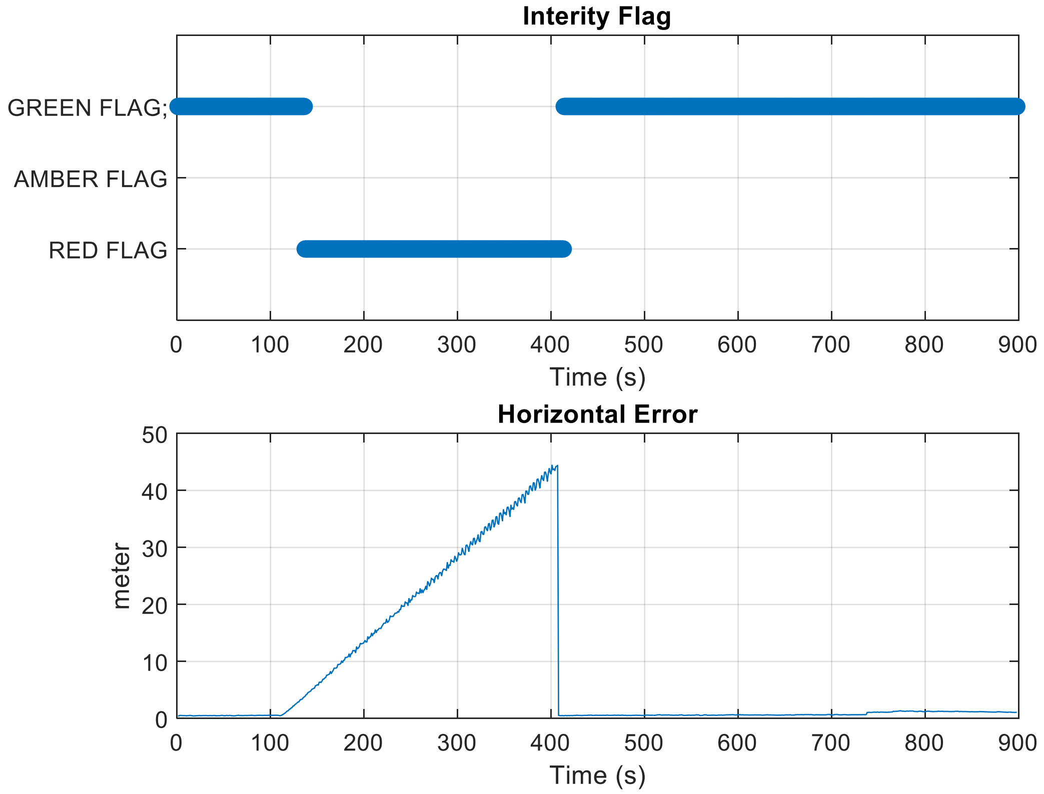


Figure 6-8 The MGRAIM Integrity Flag (above) and Horizontal Error (below).

The solution performance is summarised in

Table 6-4. For GPS L1 the horizontal error is 38.05m with a percentile of 95%.

Table 6-4 TS03 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-6.007	9.234	28.037
East	-4.807	9.029	25.938
Up	-18.93	34.374	99.765
Horizontal	8.022	12.713	38.052

Figures 6 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

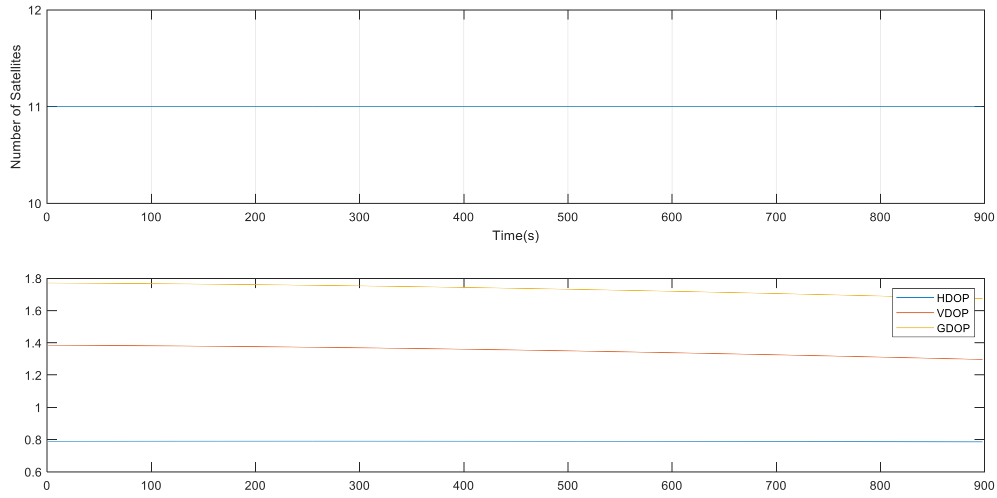


Figure 6-9 Number of SV used to generate the PVT solution and the DOP Values

6.1.2.2 TS04 – PVTI Performance Analysis (EGNOS disabled)

Figure 6-10 and Figure 6-11 show fault detection test results from Test Scenario 04 EGNOS disabled. Figure 6-10 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the "red light" integrity alarm/flag is raised. Figure 6-11, shows integrity flags and the horizontal errors within the solution generated.

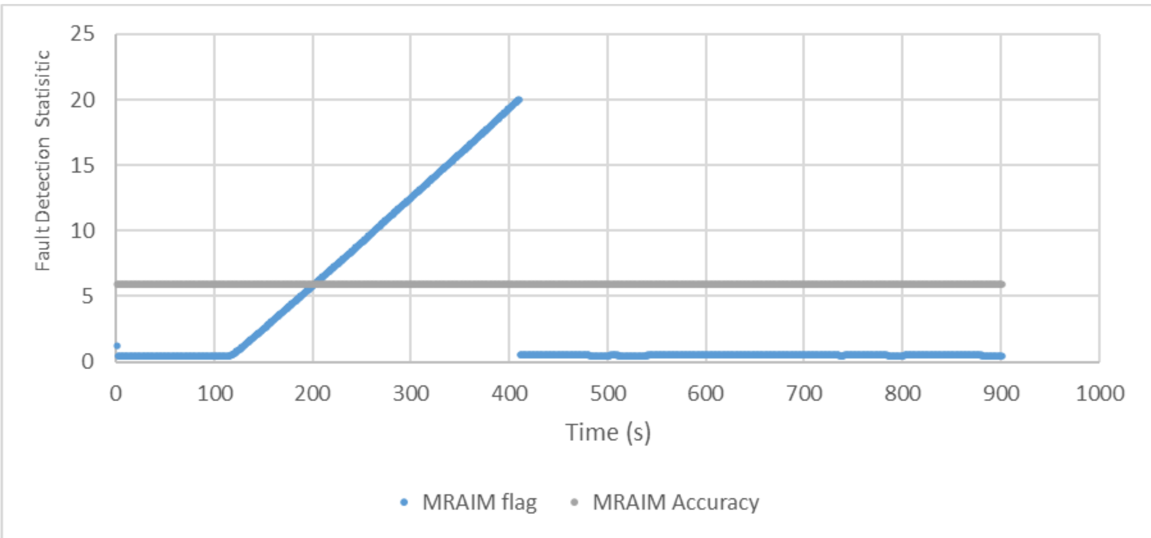


Figure 6-10 FD results from MGRAIM in ramp fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 202s where $t^2 = 6.00 > T^2 = 5.94$ and ended at time 410s where $t^2 = 20.04$

$> T^2 = 5.94$. The horizontal error values at these times were 16.91m and 53.38m respectively.

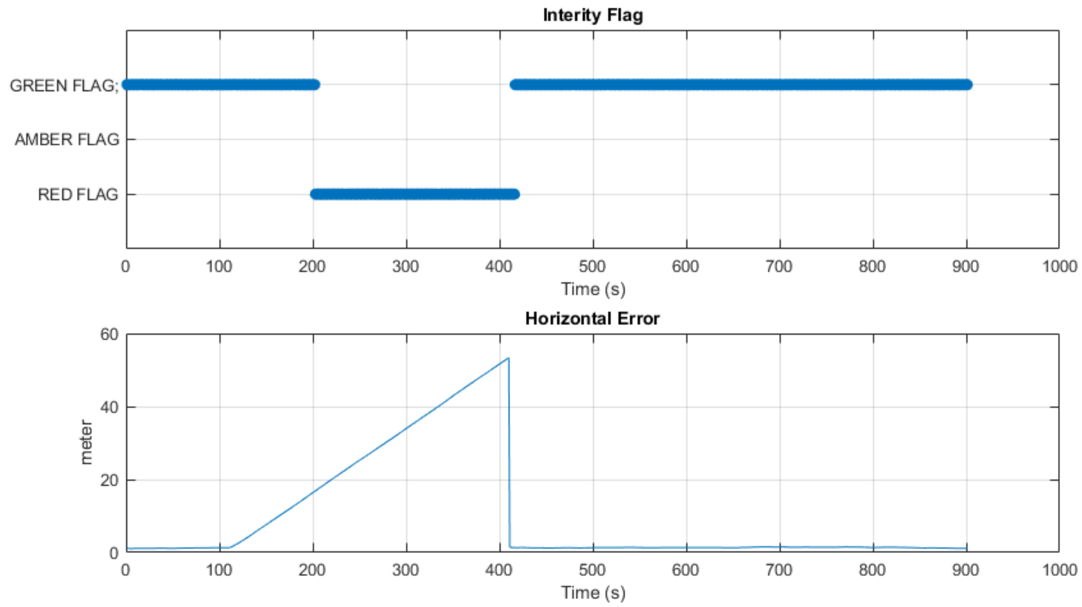


Figure 6-11 The MGRAIM Integrity Flag (above) and Horizontal Error (below).

The solution performance is summarised in Table 6-5. For GPS L1 the horizontal error is 45.61m with a percentile of 95%.

Table 6-5 TS04 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-7.836	11.456	34.935
East	-5.272	10.102	29.318
Up	-20.991	36.232	106.237
Horizontal	9.903	14.98	45.606

6.1.3 Evaluation of a ramp error on a single Low-elevation SV

This subsection shows the results generated using a smoothing constant of 100 seconds for the following scenarios:

Test Scenario	Correction mode	EGNOS mode	Fault injection	Comment
TS.05	EGNOS enabled	Legacy (GPS L1)	Single Satellite Clock failure (ramp) - Low Elevation SV	apply ramp error on a single low-elevation SV
TS.06	EGNOS disabled	N/A	Single Satellite Clock failure (ramp) - Low Elevation SV	apply ramp error on a single low-elevation SV

Table 6-6 shows the configuration parameters and values used to create the ramp fault injection dataset for a single low elevation satellite. The ramp error at the speed of 0.4m/s is injected into the original pseudo range of a single satellite from t=110s (SOW: 296228s) to t = 410s (SOW: 296528s).

Table 6-6 TS05/TS06 (SBAS) Configuration

Parameter	Value	Comment
Start time [GPS Week SOW]	[2229 296228];	represents the time and duration of the injection of the fault
End time [GPS Week SOW]	[2229 296528];	
Constellation	['G'];	The constellation on which is affected
PRN	[12];	Satellites in which the fault was injected
Range drift	[0.4m/s]	

6.1.3.1 TS05 – PVTI Performance Analysis (EGNOS Enabled)

Figure 6-12 and Figure 6-13 show fault detection test results from Test Scenario 05 EGNOS enabled. Figure 6-12 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the "red light" integrity alarm/flag is raised. Figure 6-13, shows integrity flags and the horizontal errors within the solution generated.

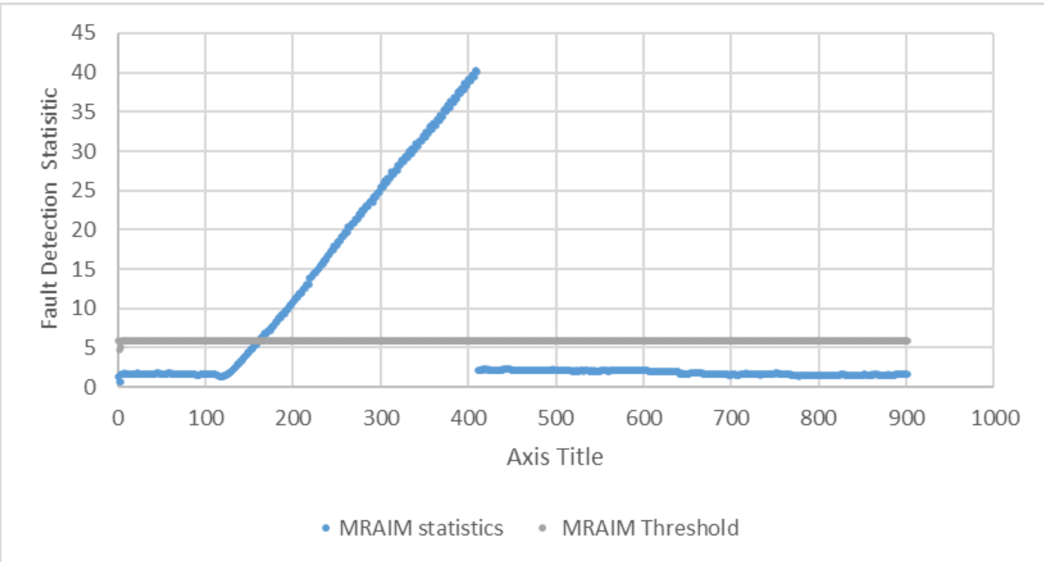


Figure 6-12 FD results from MGRAIM in ramp fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 162s where $t^2 = 6.16 > T^2 = 5.94$ and ended at time 410s where $t^2 = 40.09 > T^2 = 5.94$. The horizontal error values at these times are 2.94m and 15.69m respectively.

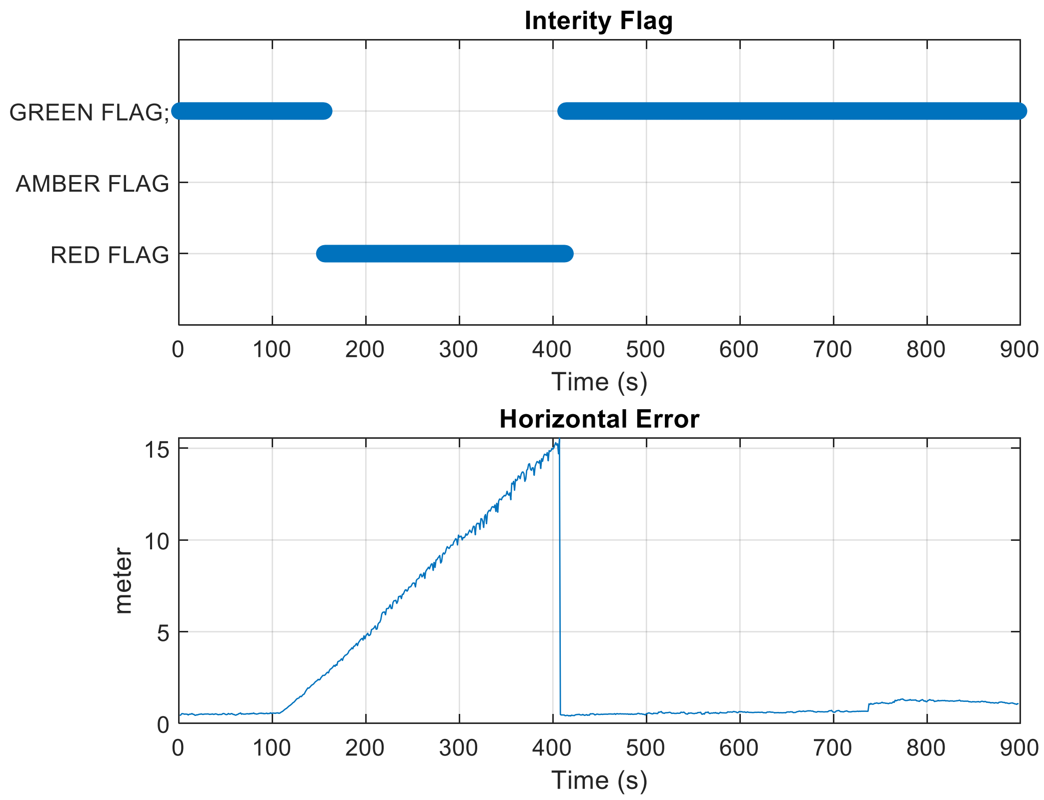


Figure 6-13 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-5. For GPS L1 the horizontal error is 13.42m with a percentile of 95%.

Table 6-7 TS05 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-2.689	3.559	11.187
East	1.625	2.295	7.242
Up	6.437	9.641	28.831
Horizontal	3.156	4.224	13.424

Figure 6-14 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

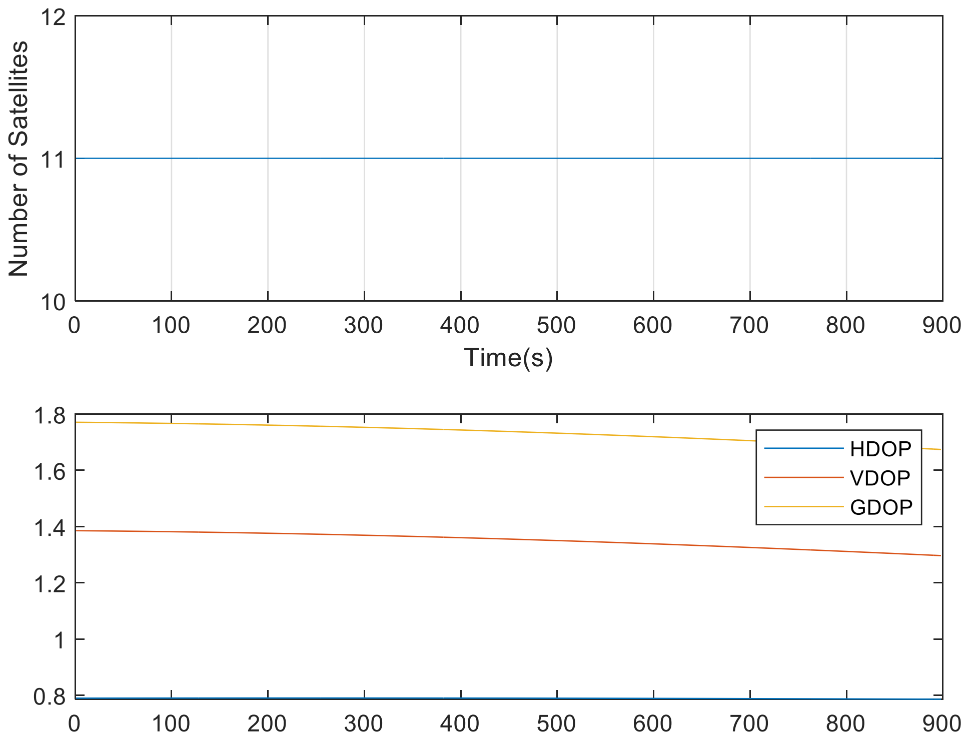


Figure 6-14 Number of SV used to generate the PVT solution and the DOP Values

6.1.3.2 TS06 – PVTI Performance Analysis (EGNOS Disabled)

Figure 6-15 and Figure 6-16 show fault detection test results from Test Scenario 06 EGNOS disabled. Figure 6-12 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the "red light" integrity alarm/flag is raised. Figure 6-16, shows integrity flags and the horizontal errors within the solution generated.

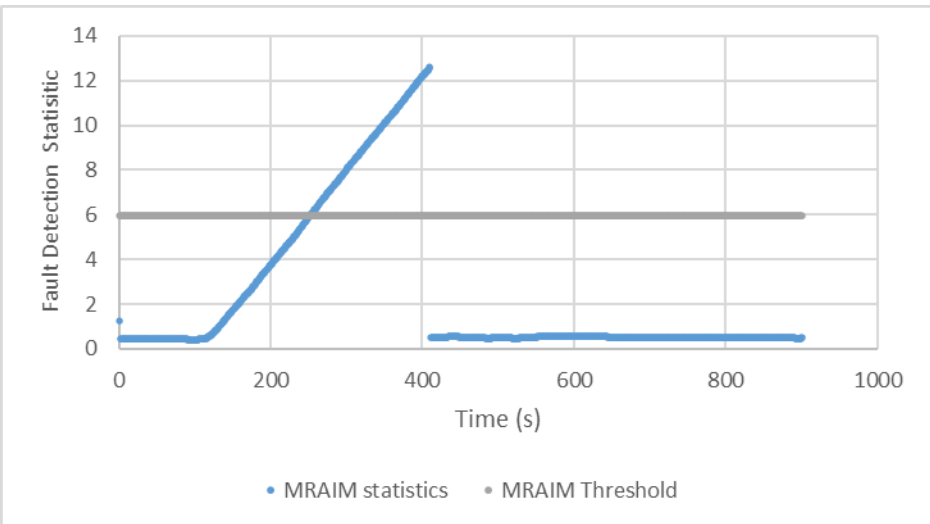


Figure 6-15 FD results from MGRAIM in ramp fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 251s where $t^2 = 5.97 > T^2 = 5.94$ and ended at time 410s where $t^2 = 12.60 > T^2 = 5.94$. The horizontal error values at these times are 7.72m and 15.18m respectively.

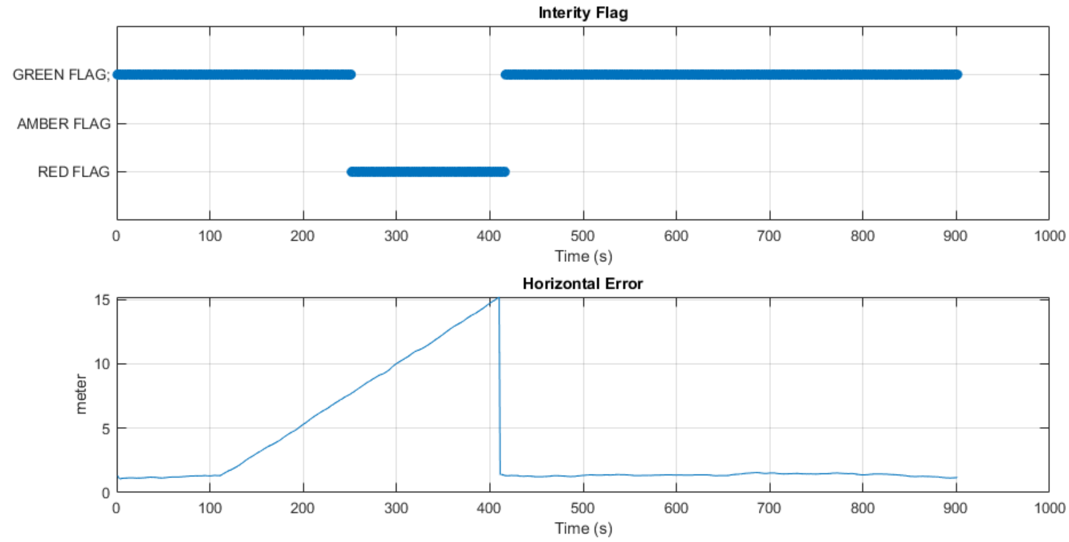


Figure 6-16 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-5. For GPS L1 the horizontal error is 13.06m with a percentile of 95%.

Table 6-8 TS06 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-3.296	3.614	11.918
East	1.452	1.638	5.341
Up	5.36	9.275	27.182
Horizontal	3.604	3.966	13.06

6.1.4 Evaluation of a bias error on a single high-elevation SV

The bias fault is a basic class of GNSS anomaly, which is usually caused by the phase jump of satellite clocks or another additive fault like signal multipath. It may lead to a substantial, virtually instant shift in the user's position even by hundreds of meters.

This subsection shows the results generated using a smoothing constant of 100 seconds based on the following test scenario:

Test Scenario	*Correction mode*	*EGNOS mode*	*Fault injection*	*Comment*
TS.07	EGNOS disabled	N/A	Single Satellite Clock failure (bias) - High Elevation SV	Applying a bias error on a single high-elevation SV
TS.08	EGNOS enabled	Legacy (GPS L1)	Single Satellite Clock failure	apply bias error on a single high-elevation SV

			(bias) - High Elevation SV	

The subsection will look at the results generated using the minimum and a large detectable bias error that will raise a RED integrity flag as well as a bias value that will raise GREEN flag these values were extracted from the ramp error analysis conducted in the previous subsection. Table 6-9 shows the configuration parameters and values used to create the bias fault injection dataset. A fault bias of 35m, 36.8m and 100m was injected at times t=110s, t=908s and t =1808s in a high-elevation satellite G03 in the EGNOS disabled case.

Table 6-9 TS07 Configuration EGNOS disabled case

Parameter	***Value***	***Comment***
Start time [SOW]	[297026, 296228, 297926]	represents the time and duration of the injection of the fault
End time [SOW]	[297326, 296528, 298226]	
Constellation	['G'];	The constellation on which is affected
PRN	[3];	Satellites in which the fault was injected
Range bias	[35, 36.8, 100];	fault bias values injected into the RINEX file.

Table 6-10 shows the configuration parameters and values used to create the bias fault injection dataset. A fault bias of 11m, 11.6m and 100m was injected at times t=110s, t=908s and t =1808s in a high-elevation satellite G03 in the EGNOS disabled case.

Table 6-10 TS08 Configuration EGNOS enabled case

Parameter	***Value***	***Comment***
Start time [SOW]	[297026, 296228, 297926]	represents the time and duration of the injection of the fault
End time [SOW]	[297326, 296528, 298226]	
Constellation	['G'];	The constellation on which is affected
PRN	[3];	Satellites in which the fault was injected
Range bias	[11,11.6,100]	fault bias values injected into the RINEX file.

6.1.4.1 TS07– PVTI Performance Analysis (EGNOS Disabled)

Figure 6-17 and Figure 6-18 show fault detection test results from Test Scenario 07 EGNOS disabled. Figure 6-17 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the “red light” integrity alarm/flag is raised. Figure 6-18, shows integrity flags and the horizontal errors within the solution generated.

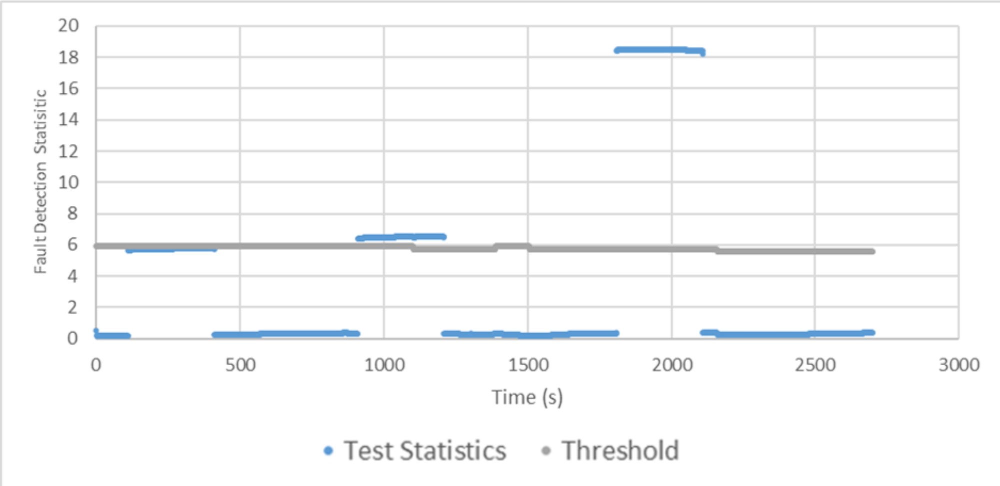


Figure 6-17 FD results from MGRAIM in ramp fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 907s where $t^2 = 6.43 > T^2 = 5.94$ and ended at time 1206s where $t^2 = 6.49 > T^2 = 5.75$. The horizontal error values at these times are 15.89m and 15.75m respectively. The red flag was raised at time 1807s where $t^2 = 18.45 > T^2 = 5.75$ and ended at time 2106s where $t^2 = 18.23 > T^2 = 5.75$. The horizontal error values at these times are 40.88 and 39.01 respectively.

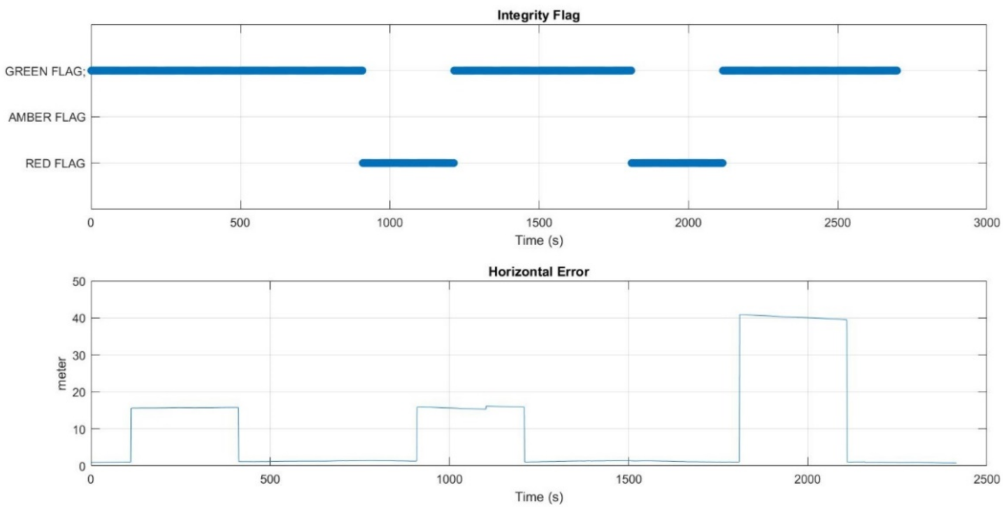


Figure 6-18 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-5. For GPS L1 the horizontal error is 40.32m with a percentile of 95%.

Table 6-11 TS07 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-6.323	7.728	22.836
East	-6.147	11.227	33.504
Up	-13.759	16.333	38.721
Horizontal	9.647	13.057	40.323

Figure 6-19 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

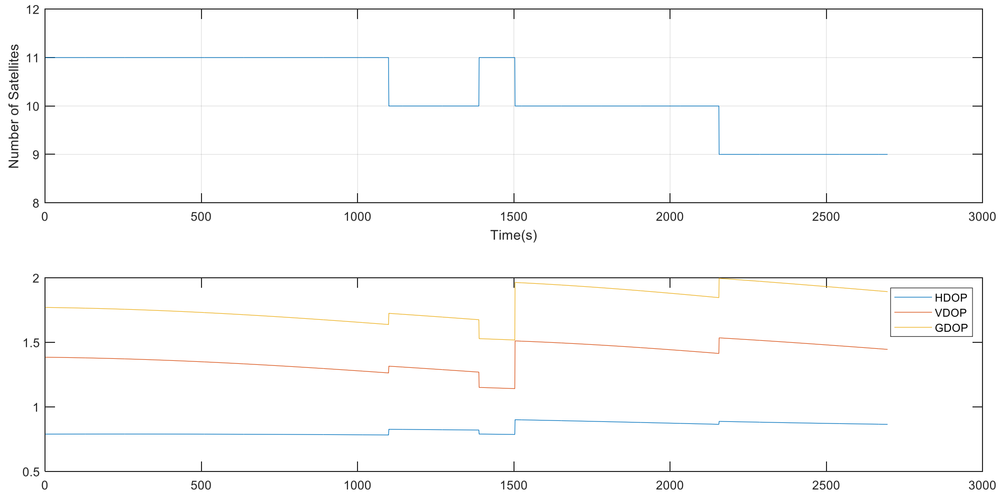


Figure 6-19 Number of SV used to generate the PVT solution and the DOP Values

6.1.4.2 TS07 – PVTI Performance Analysis (EGNOS Enabled)

Figure 6-20 and Figure 6-21 show fault detection test results from Test Scenario 08 EGNOS enabled. Figure 6-20 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the "red light" integrity alarm/flag is raised. Figure 6-21, shows integrity flags and the horizontal errors within the solution generated.

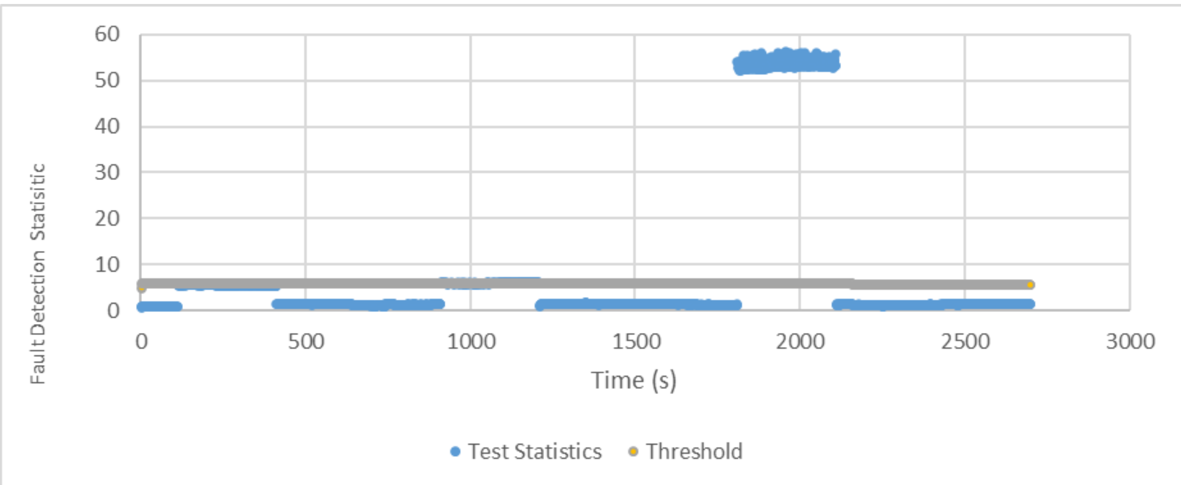


Figure 6-20 FD results from MGRAIM in ramp fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 907s where $t^2 = 5.95 > T^2 = 5.94$ and ended at time 1206s where $t^2 = 5.91 > T^2 = 5.75$. The horizontal error values at these times are 4.28m and 3.875m respectively. The red flag was raised at time 1807s where $t^2 = 54.09 > T^2 = 5.75$ and ended at time 2106s where $t^2 = 55.78 > T^2 = 5.75$. The horizontal error values at these times are 33.99m and 36.03m respectively.

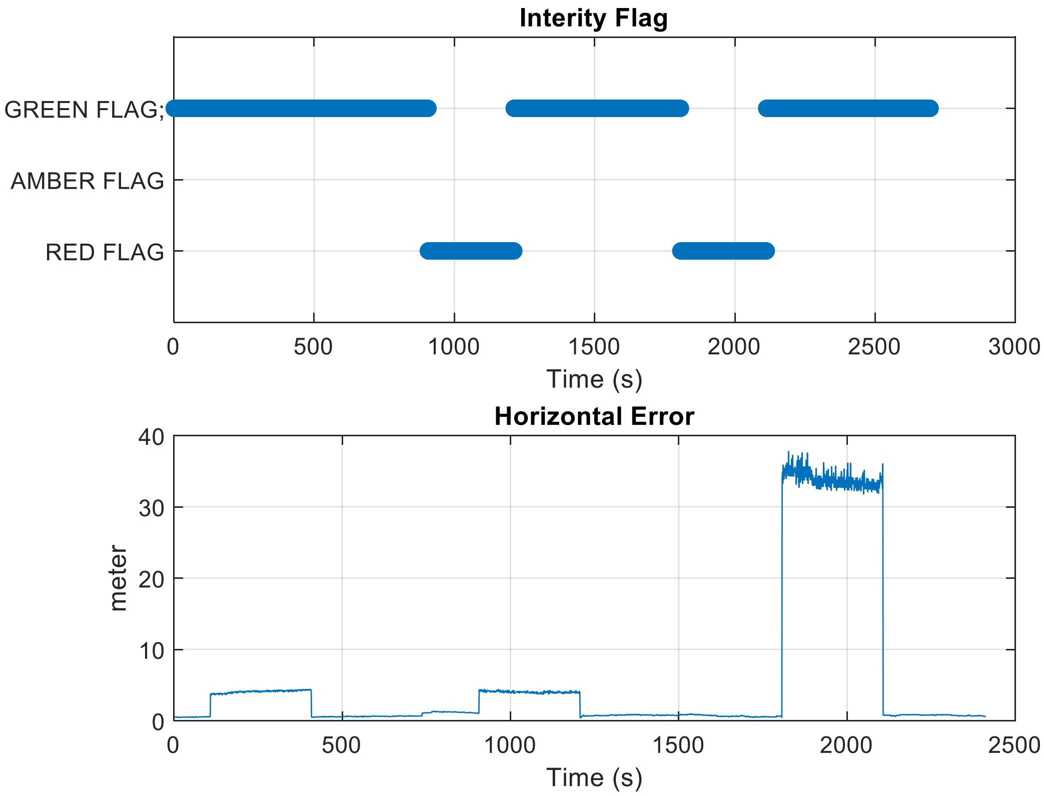


Figure 6-21 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-12. For GPS L1 the horizontal error is 34.03m with a percentile of 95%.

Table 6-12 TS08 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-3.32	6.135	19.428
East	-3.69	9.213	27.94
Up	-8.351	14.682	46.885
Horizontal	5.679	10.719	34.029

Figure 6-22 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

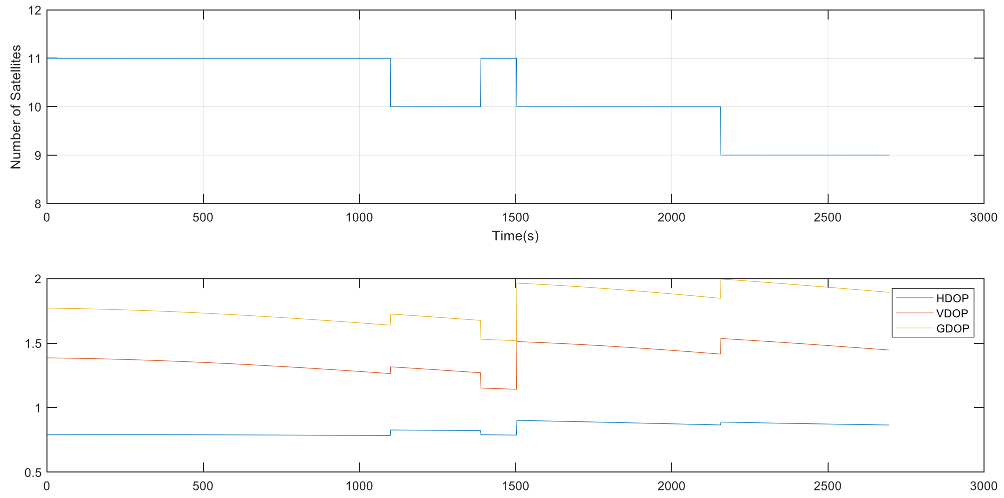


Figure 6-22 Number of SV used to generate the PVT solution and the DOP Values

To test the full EGNOS capabilities within the positioning algorithm because the faults were injected the RINEX level the associated EGNOS message file was manually edited to reflect the status of the affected satellite. To achieve this the satellite on which the fault was injected was given the Don't Use: UDREI=15 designation which indicates that an inconsistency has been found for this satellite (alarm situation) or the estimated fast correction is greater than 256.0 m.

Using the fault-injected dataset from TS08 and the edited EGNOS message file Figure 6-23 shows fault detection test results from Test Scenario 08a EGNOS enabled. Figure 6-23, shows integrity flags and the horizontal errors within the solution generated. The GREEN integrity flag was raised which means that the test statistic computed was less than the threshold. This since the satellite with the bias injected was removed from the PVTI solution computation.

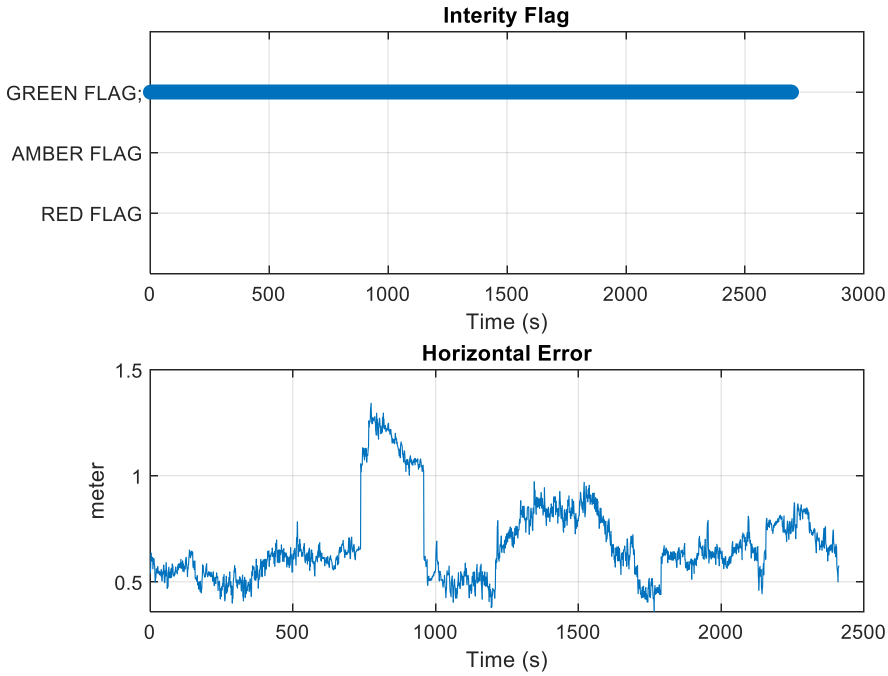


Figure 6-23 The MGRAIM Integrity Flag (above) and Horizontal Error

The solution performance is summarised in Table 6-13. For GPS L1 the horizontal error is 1.21m with a percentile of 95%.

Table 6-13 TS08a - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-0.251	0.258	0.717
East	0.568	0.225	0.879
Up	-0.249	0.374	0.818
Horizontal	0.683	0.189	1.121

Figure 6-24 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

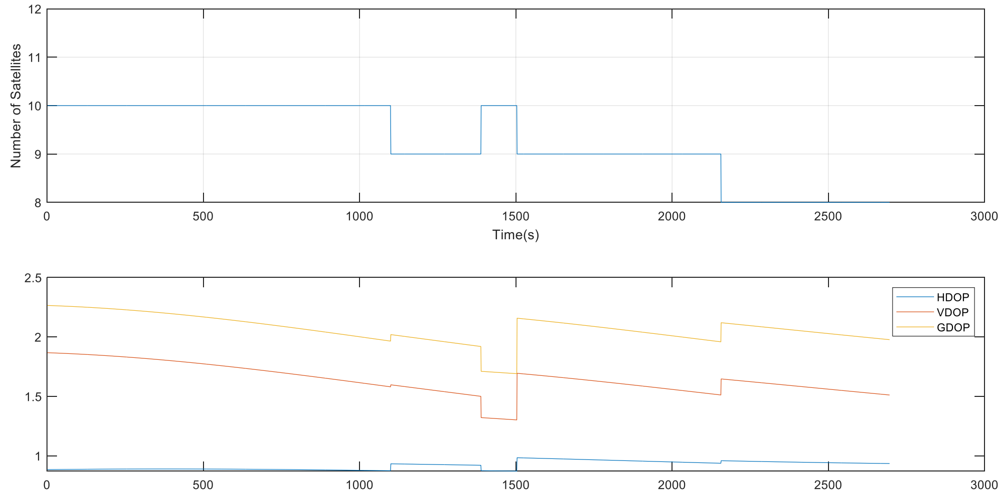


Figure 6-24 Number of SV used to generate the PVT solution vs NSATs in view and the DOP Values

It has been observed that the faulty satellite was excluded from the PVT solution computation. It can be seen that between 10 to 8 satellites were used out of the 11 to 9 satellites that were in view at some point throughout the dataset for the position computation. Also, the accuracy of TS08a improved over the solution accuracy compute in TS08. Finally, a GREEN integrityy flag was raised which indicates that the test statistic did not exceed the detection threshold ($t^2 < T^2$).

6.1.5 Evaluation of a bias error on a single Low-elevation SV

The bias fault is a basic class of GNSS anomaly, which is usually caused by the phase jump of satellite clocks or another additive fault like signal multipath. It may lead to a substantial, virtually instant shift in the user's position even by hundreds of meters.

This subsection shows the results generated using a smoothing constant of 100 seconds based on the following test scenario:

Test Scenario	Correction mode	EGNOS mode	Fault injection	Comment
TS.09	EGNOS disabled	N/A	Single Satellite Clock failure (bias) -Low Elevation SV	Applying a bias error on a single high-elevation SV
TS.10	EGNOS enabled	Legacy (GPS L1)	Single Satellite Clock failure (bias) -Low Elevation SV	apply bias error on a single high-elevation SV

The subsection will look at the results generated using the minimum and a large detectable bias error that will raise a RED integrity flag as well as a bias value that will raise GREEN flag these values were extracted from the ramp error analysis conducted in the previous subsection. These values were extracted from the ramp error analysis conducted in the previous subsection. Table 6-14 shows the configuration parameters and values used to create the bias fault injection dataset. A fault bias of 50m, 56.4m, and 100m was injected at times t=110s, t=908s and t =1808s in a low-elevation satellite G12.

Table 6-14 TS09 Configuration EGNOS disabled

Parameter	Value	Comment
Start time [SOW]	[297026, 296228, 297926]	represents the time and duration of the injection of the fault
End time [SOW]	[297326, 296528, 298226]	
Constellation	['G'];	The constellation on which is affected
PRN	[12];	Satellites in which the fault was injected
Range bias	[50, 56.4,100];	fault bias values injected into the RINEX file.

Table 6-15 shows the configuration parameters and values used to create the bias fault injection dataset. A fault bias of 18m, 20.8m and 100m was injected at times t=110s, t=908s and t =1808s in a high-elevation satellite G03 in the EGNOS disabled case.

Table 6-15 TS10 Configuration EGNOS enabled

Parameter	Value	Comment
Start time [SOW]	[297026, 296228, 297926]	represents the time and duration of the injection of the fault
End time [SOW]	[297326, 296528, 298226]	
Constellation	['G'];	The constellation on which is affected
PRN	[12];	Satellites in which the fault was injected
Range bias	[18, 20.8,100];	fault bias values injected into the RINEX file.

6.1.5.1 TS09 – PVTI Performance Analysis (EGNOS Disabled)

The subsection will look at the results generated using a minimum and maximum detectable bias errors, these values were extracted from the ramp error analysis

Figure 6-25 and Figure 6-26 show fault detection test results from Test Scenario 09 EGNOS disabled. Figure 6-25 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the "red light" integrity alarm/flag is raised. Figure 6-26, shows integrity flags and the horizontal errors within the solution generated.

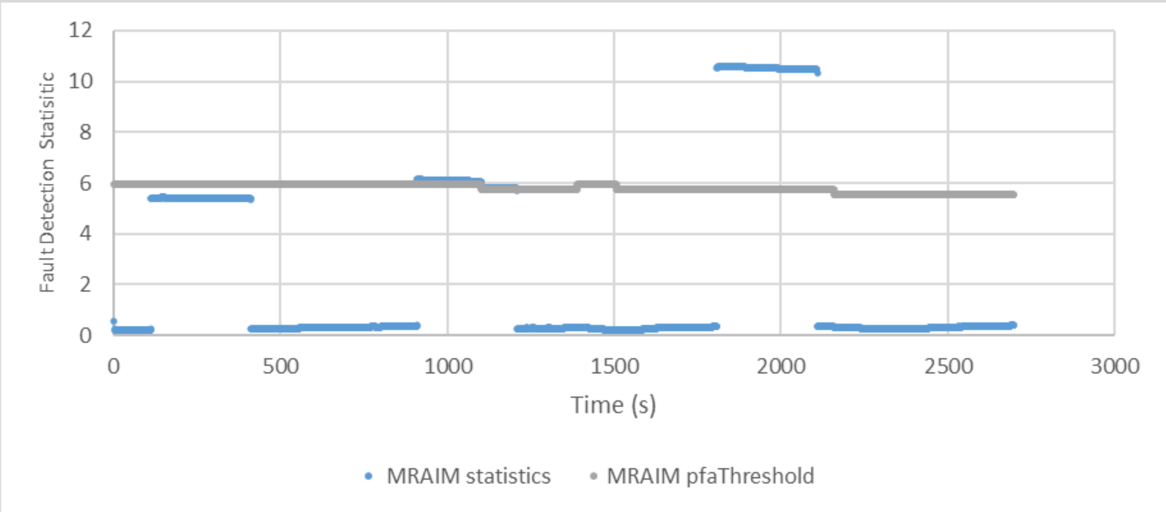


Figure 6-25 FD results from MGRAIM in ramp fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 909s where $t^2 = 6.15 > T^2 = 5.94$ and ended at time 1207s where $t^2 = 5.78 > T^2 = 5.75$. The horizontal error values at these times are 8.01m and 8.63m respectively. The red flag was raised at time 1808s where $t^2 = 10.52 > T^2 = 5.75$ and ended at time 2108s where $t^2 = 10.34 > T^2 = 5.75$. The horizontal error values at these times are 10.07m and 9.92m respectively.

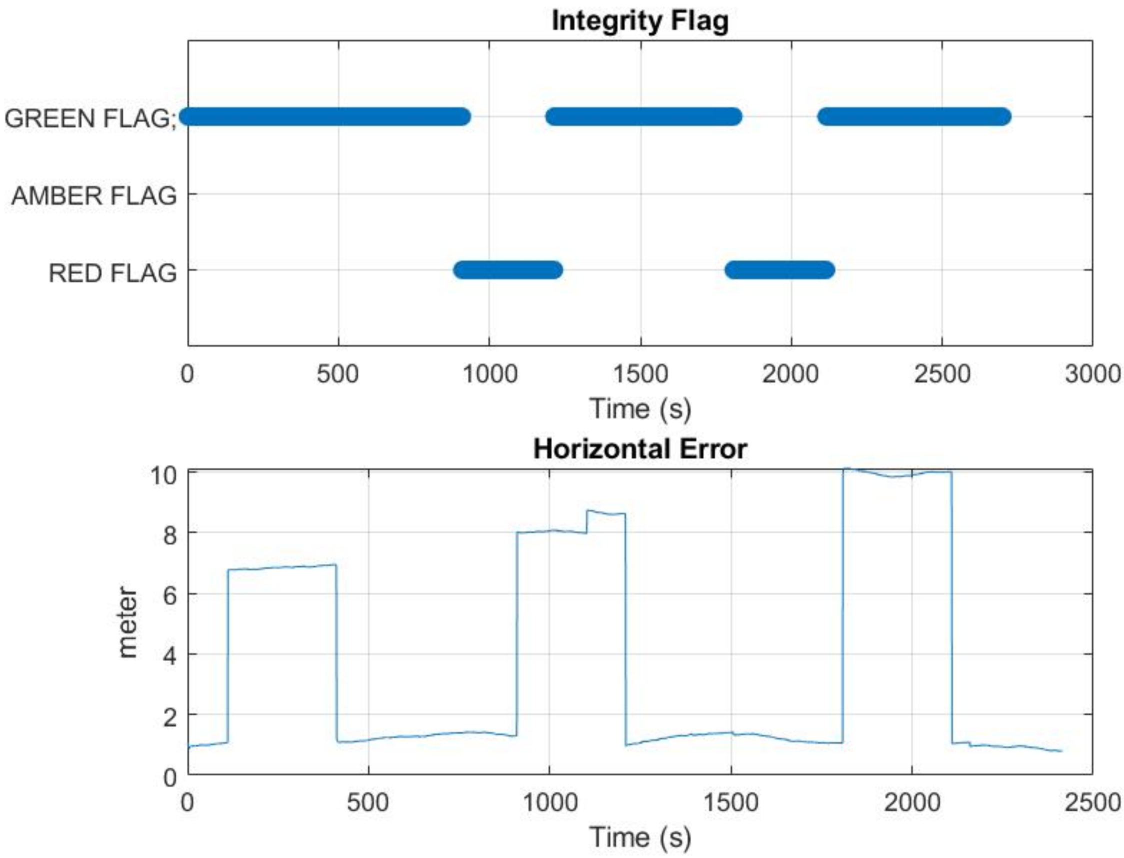


Figure 6-26 The MGRAIM Integrity Flag (above) and Horizontal Error (below)

The solution performance is summarised in Table 6-16. For GPS L1 the horizontal error is 9.996m with a percentile of 95%.

Table 6-16 TS09 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-3.359	3.368	9.345
East	1.788	1.317	4.165
Up	6.075	10.452	27.809
Horizontal	3.851	3.568	9.996

Figure 6-27 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

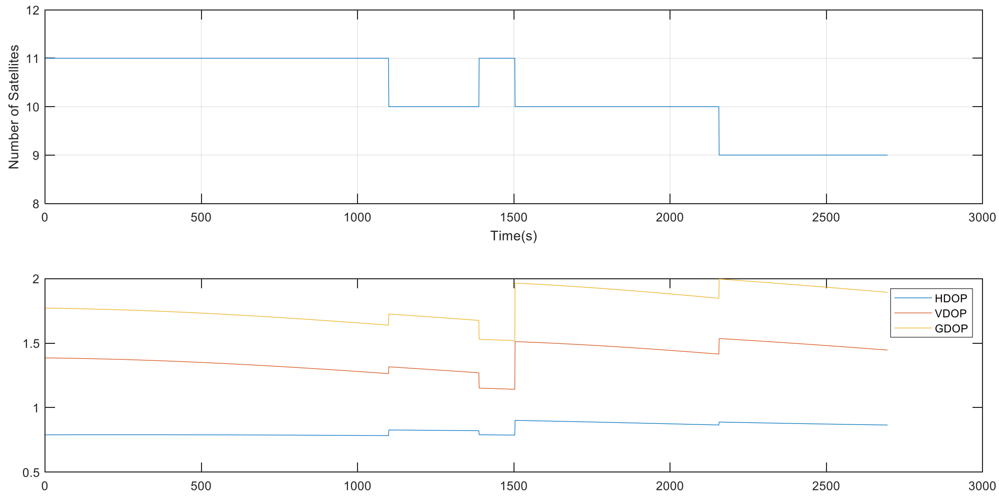


Figure 6-27 Number of SV used to generate the PVT solution and the DOP Values

6.1.5.2 TS.10 – PVTI Performance Analysis (EGNOS ENABLED)

Figure 6-28 and Figure 6-29 show fault detection test results from Test Scenario 09 EGNOS enabled. Figure 6-28 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the "red light" integrity alarm/flag is raised. Figure 6-29, shows integrity flags and the horizontal errors within the solution generated.

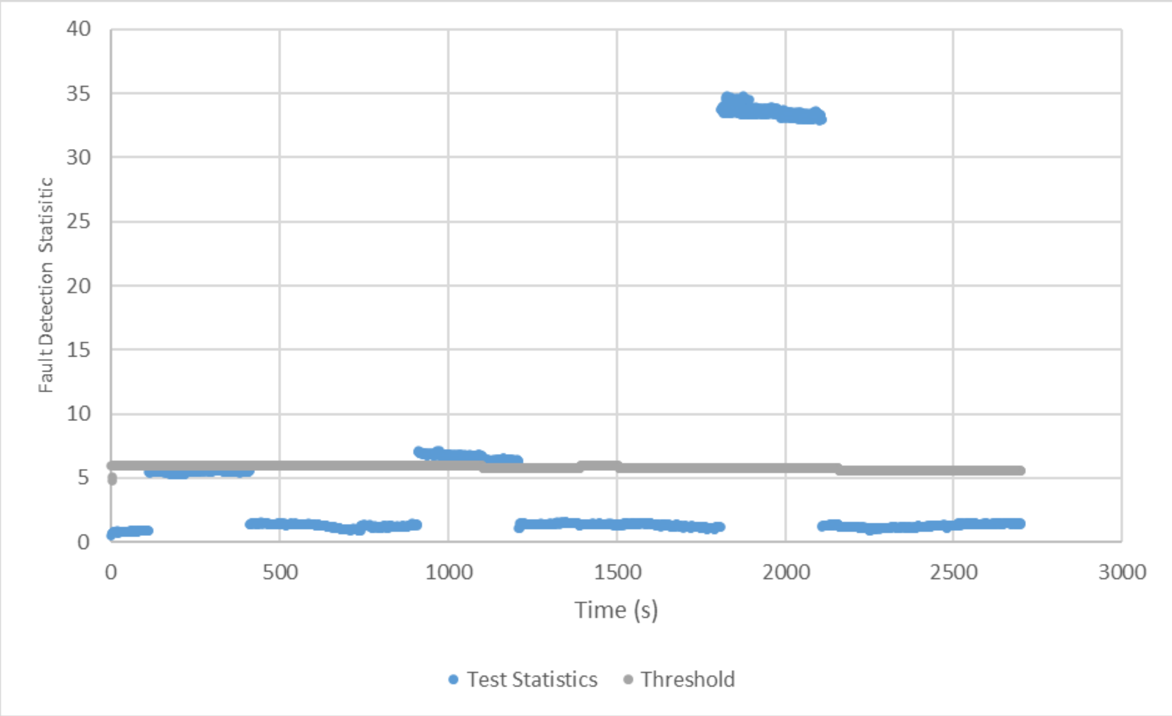


Figure 6-28 FD results from MGRAIM in ramp fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 909s where $t^2 = 7.00 > T^2 = 5.94$ and ended at time 1207s where $t^2 = 6.24 > T^2 = 5.75$. The horizontal error values at these times are 3.72m and 2.99m respectively. The red flag was raised at time 1808s where $t^2 = 33.76 > T^2 = 5.75$ and ended at time 2108s where $t^2 = 32.98 > T^2 = 5.75$. The horizontal error values at these times are 10.017m and 9.94m respectively.

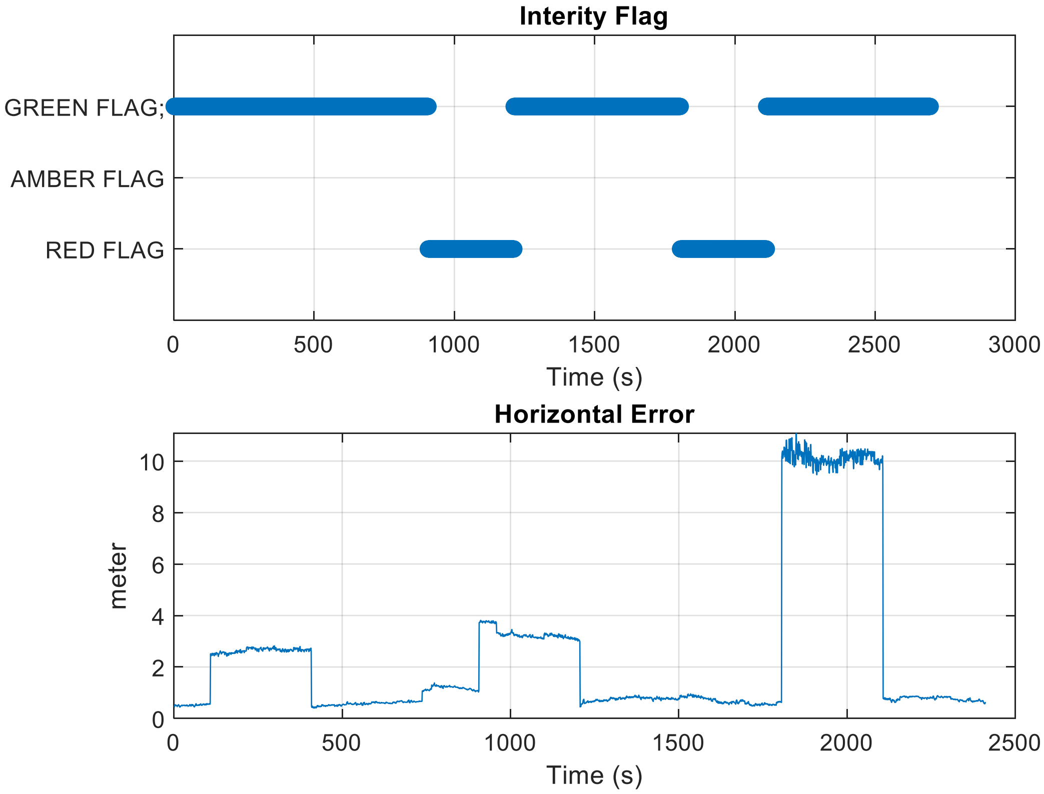


Figure 6-29 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-17. For GPS L1 the horizontal error is 10.20m with a percentile of 95%.

Table 6-17 TS10 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	**STD (m)**	**95% (m)**
North	-1.825	2.774	8.776
East	1.5	1.458	5.178
Up	4.972	9.748	29.921
Horizontal	2.46	3.058	10.201

Figure 6-30 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

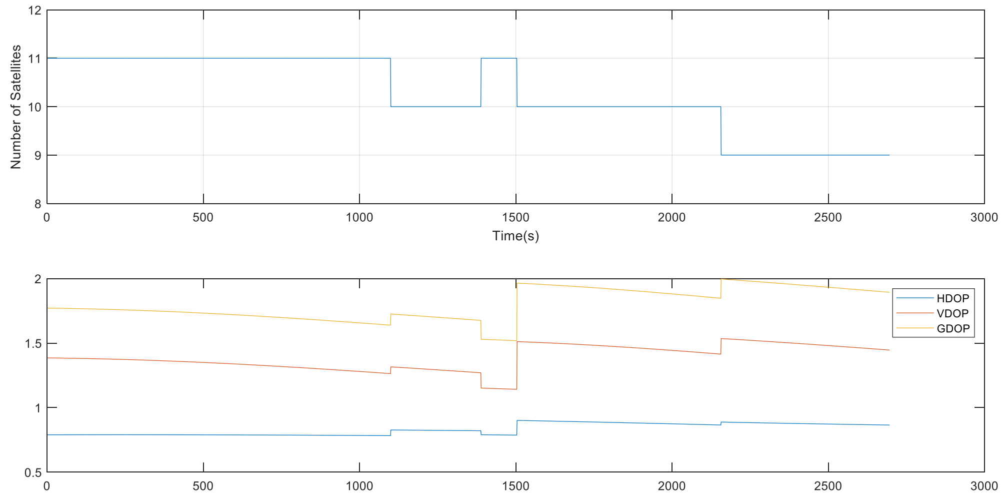


Figure 6-30 Number of SV used to generate the PVT solution and the DOP Values

To test the full EGNOS capabilities within the positioning algorithm because the faults were injected at the RINEX level the associated EGNOS message file was manually edited to reflect the status of the affected satellite. To achieve this the satellite on which the fault was injected was given the Don't Use: UDREI=15 designation which indicates that an inconsistency has been found for this satellite (alarm situation) or the estimated fast correction is greater than 256.0 m.

Using the fault-injected dataset from TS10 and the edited EGNOS message file Figure 6-31 shows fault detection test results from Test Scenario 10a EGNOS enabled. Figure 6-31, shows integrity flags and the horizontal errors within the solution generated. The GREEN integrity flag was raised which means that the test statistic computed was less than the threshold. This since the satellite with the bias injected was removed from the PVTI solution computation.

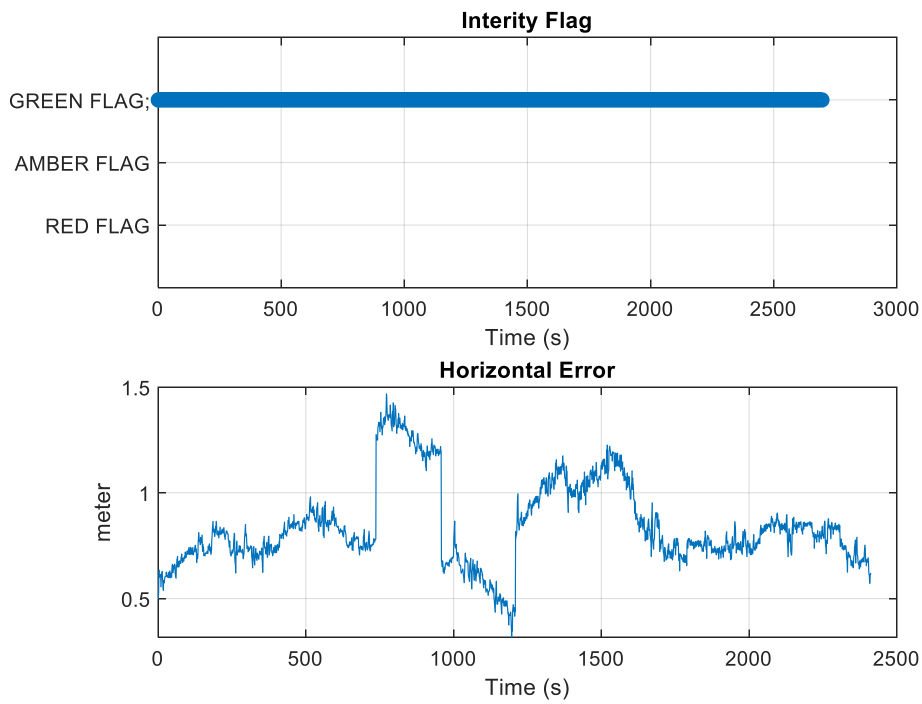


Figure 6-31 The MGRAIM Integrity Flag (above) and Horizontal Error

The solution performance is summarised in Table 6-5. For GPS L1 the horizontal error is 10.20m with a percentile of 95%.

Table 6-18 TS10a - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-0.393	0.237	0.782
East	0.71	0.188	1.010
Up	0.376	0.386	1.080
Horizontal	0.843	0.199	1.259

Figure 6-14 illustrates the number of satellites used to compute the PVT solution and the computed DOP.

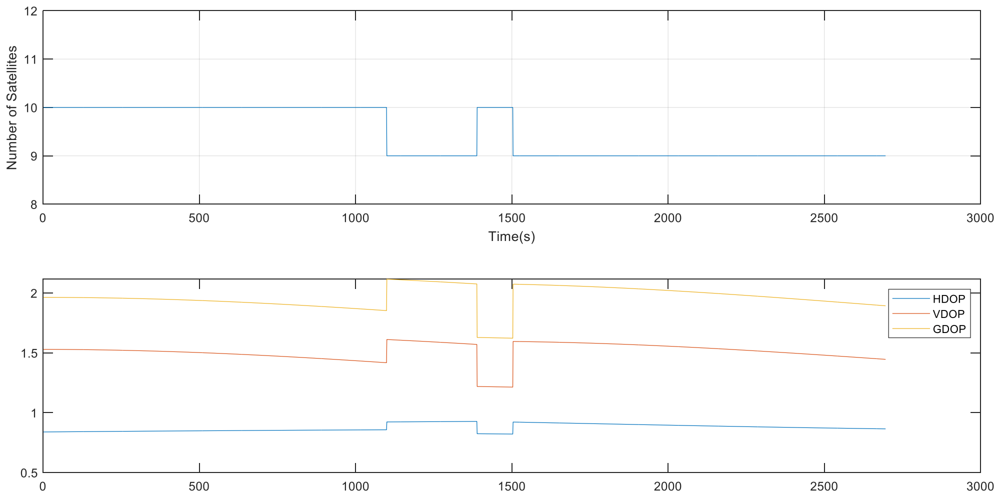


Figure 6-32 Number of SV used to generate the PVT solution vs NSATs in view and the DOP Values

It has been observed that the faulty satellite was excluded from the PVT solution computation. Figure 6-32 show that between 10 or 9 satellites were used out of the 10 to 11 satellites that were in view at some point throughout the dataset for the position computation. Also, the accuracy of TS* improved out the solution accuracy compute in TS 10. Finally, a GREEN integrity flag was raised which indicates that the test statistic did not exceed the detection threshold ($t^2 < T^2$).

6.1.6 Evaluation of an ephemeris error on a single high-elevation SV

The ephemeris is the satellite coordinate system. It tells the receiver where the satellite is at an instant of time. GPS receivers calculate coordinates relative to the known locations of satellites in space, a complex task that involves knowing the shapes of satellite orbits as well as their velocities, neither of which is constant. The GPS Control Segment monitors satellite locations at all times, calculates orbit eccentricities, and compiles these deviations in documents called ephemerides. An ephemeris is compiled for each satellite and broadcast with the satellite signal. There is always a certain amount of age in the ephemerides and that means that the position of the satellite expressed in its ephemeris at the moment of observation cannot be perfect. So orbital bias could be thought of as the error in the broadcast ephemeris.

Even with the corrections from the GNSS ground control system, there are still small errors in the orbit that can result in up to ±2.5 metres of position error.

This subsection shows the results generated using a smoothing constant of 100 seconds based on the following test scenario:

Test Scenario	***Correction mode***	***EGNOS mode***	***Fault injection***	***Comment***
TS.11	EGNOS disabled	N/A	Single Satellite Bad Ephemeris Upload - High Elevation SV	Manually edit an ephemeris parameter within the Broadcast Navigation Message (e.g. the LAAN value)
TS.12	EGNOS enabled	Legacy (GPS L1)	Single Satellite Bad Ephemeris Upload - High Elevation SV	

Table 6-19 shows the configuration parameters and values used to create the bias fault injection dataset. For this test scenario the longitude of the ascending node parameter on a high elevation was modified within the broadcast navigation message was from its original value *.248039365746D+01 to .148039365746D+01*

Table 6-19 TS.11/TS.12 Configuration

Parameter	***Value***	***Comment***
Constellation	['G'];	The constellation on which is affected
PRN	[3];	Satellites in which the fault was injected
Ephemeris – The longitude of the ascending node Ω_0)	*From:0.248039365746D+01 to 0.148039365746D+01*	This is one of the orbital elements used to specify the orbit of an object in space.

6.1.6.1 TS11 – PVTI Performance Analysis (EGNOS Disabled)

Figure 6-33 and Figure 6-34 show fault detection test results from Test Scenario 11 EGNOS disabled. Figure 6-33 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the “red light” integrity alarm/flag is raised. Figure 6-34, shows integrity flags and the horizontal errors within the solution generated.

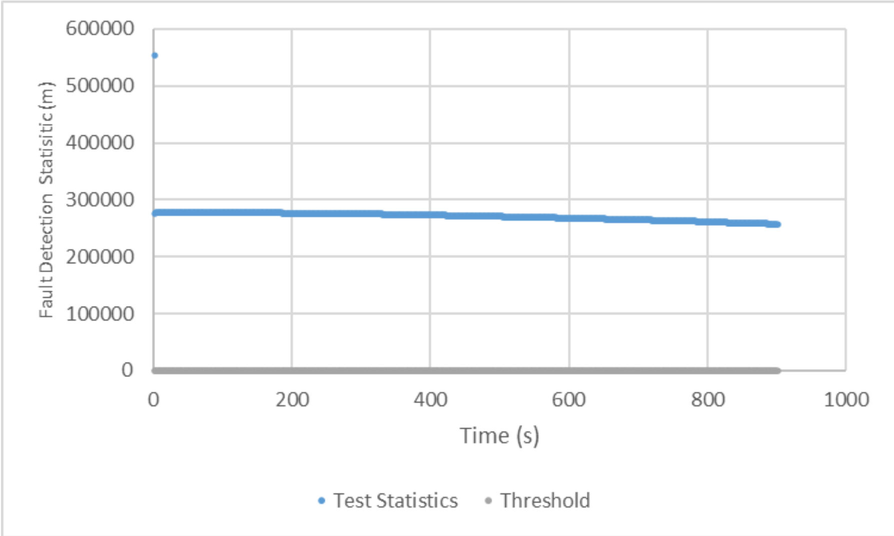


Figure 6-33 FD results from MGRAIM in Ephemeris fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised for the entire duration of the dataset as the test statistics exceed the threshold value of 5.95.

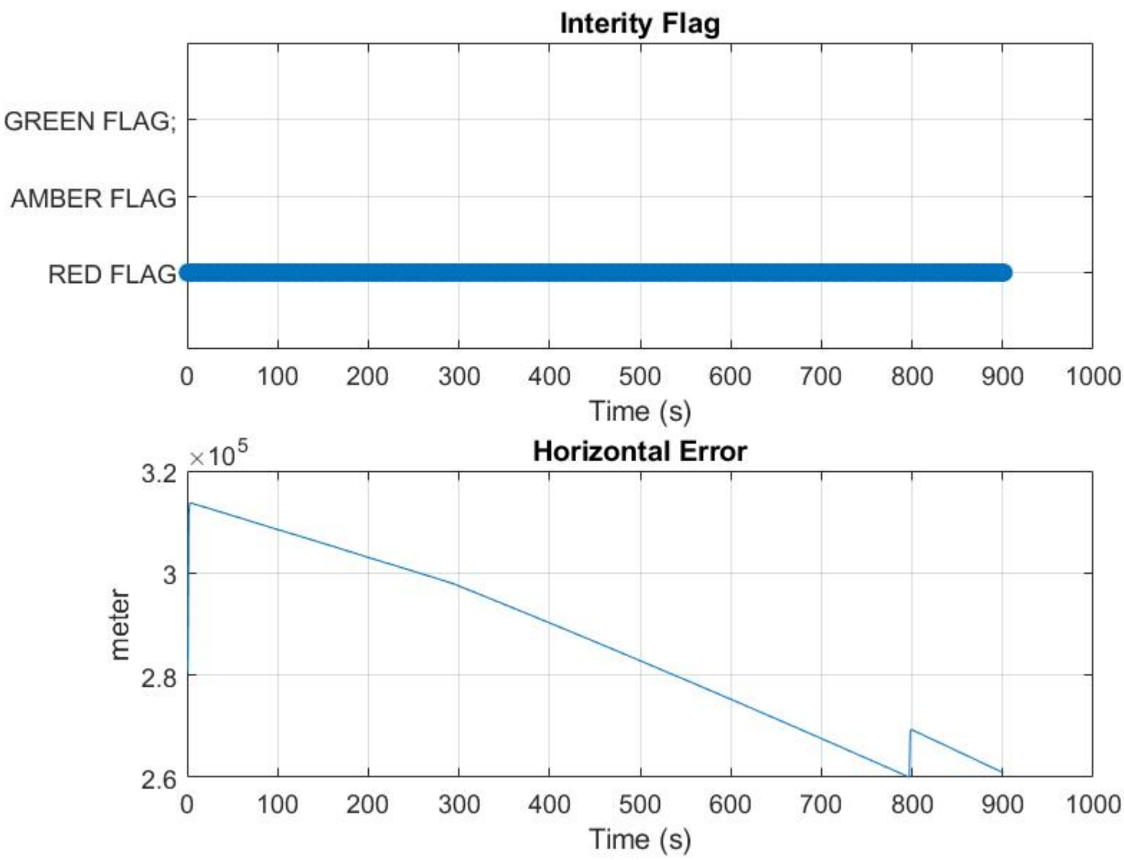


Figure 6-34 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-20. For GPS L1 the horizontal error is 40.32m with a percentile of 95%.

Table 6-20 TS11 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-64827.4	24642.28	103955.6
East	-277993	11469.63	293546.7
Up	-34379.2	98835.06	172462.6
Horizontal	286253.8	16721.01	311433.6

Figure 6-35 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

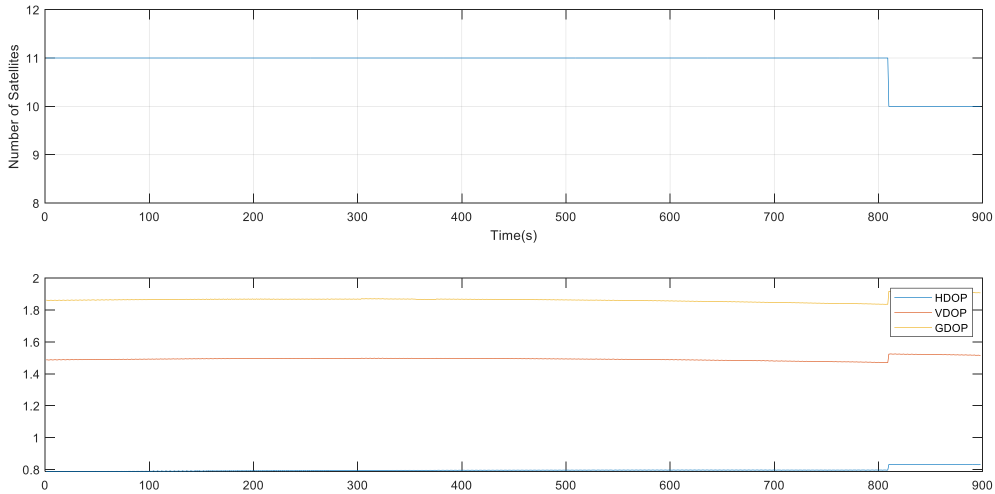


Figure 6-35 Number of SV used to generate the PVT solution and the DOP Values

6.1.6.2 TS12 – PVTI Performance Analysis (EGNOS Enabled)

Figure 6-36 and Figure 6-37 show fault detection test results from Test Scenario 12 EGNOS enabled. Figure 6-36 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the “red light” integrity alarm/flag is raised. Figure 6-37, shows integrity flags and the horizontal errors within the solution generated.

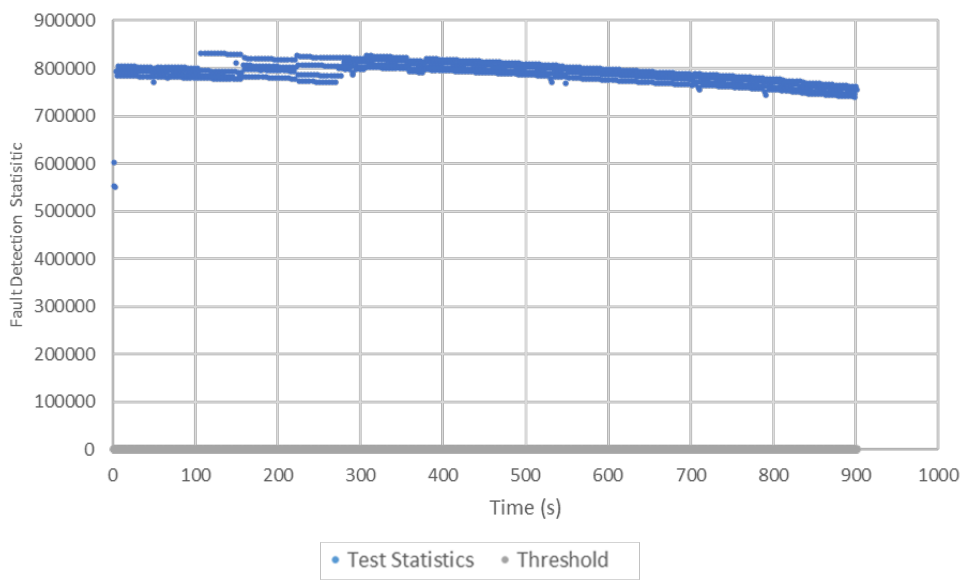


Figure 6-36 FD results from MGRAIM in Ephemeris fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised for the entire duration of the dataset as it can be seen that the test statistics exceeds the threshold value of 5.95.

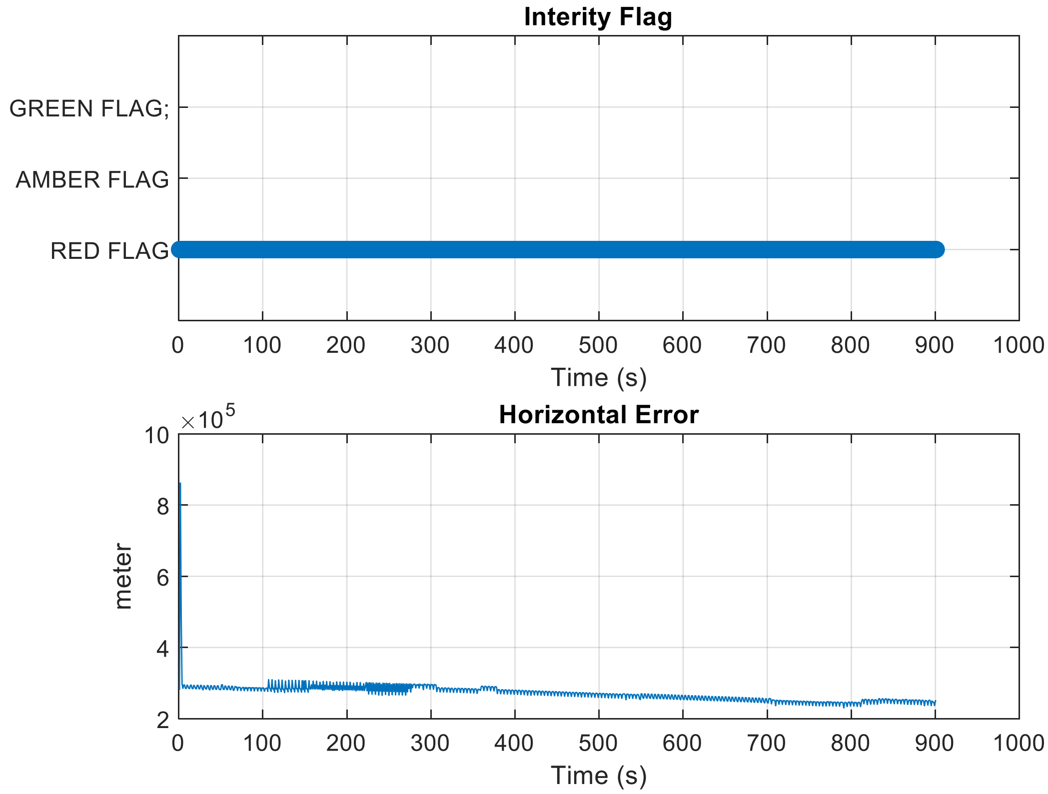


Figure 6-37 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-21

Table 6-21 TS12 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-54796	20010.52	80641.21
East	-265045	24899.73	290469.6
Up	-7683.88	86688.4	144294.1
Horizontal	271119.7	27675.95	298800.1

Figure 6-38 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

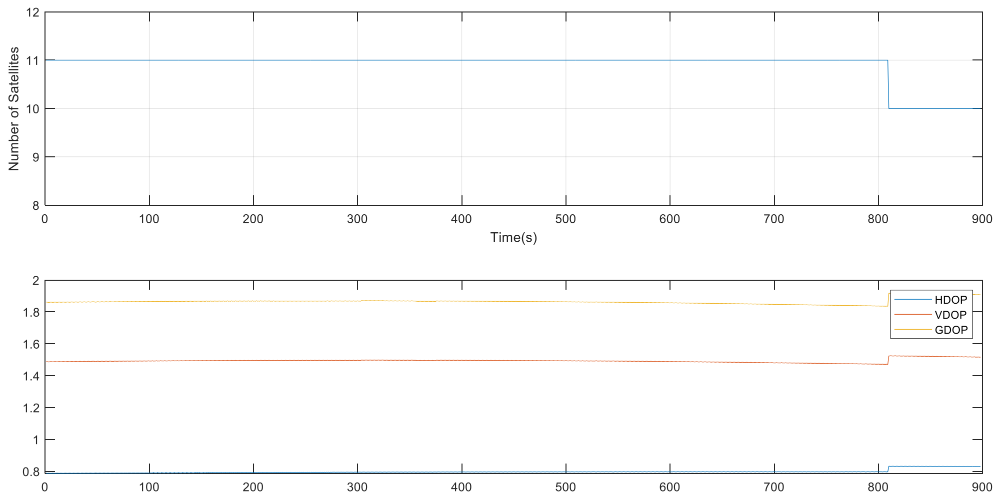


Figure 6-38 Number of SV used to generate the PVT solution and the DOP Values

6.1.7 Evaluation of a Multipath Error on a single high elevation SV

Multipath is a very localised effect, which depends only on the local environment surrounding the antenna. GNSS multipath is caused by the reception of signals arrived not only directly from satellites, but also reflected or diffracted the local objects. These signal components arrive with a certain delay, phase, and amplitude difference relative to the line-of-sight (LOS) component Multipath results in an error in pseudo range measurements and thus affects the positioning accuracy since the multipath signal takes a longer path than the direct signal resulting in pseudorange (code phase) errors of tens of metres.

This subsection shows the results generated using a smoothing constant of 100 seconds based on the following test scenario:

Test Scenario	*Correction mode*	*EGNOS mode*	*Fault injection*
TS.13	EGNOS disabled	N/A	Applying multipath error on a single high-elevation SV
TS.14	EGNOS disabled	N/A	Applying multipath error on a single low -elevation SV

Table 6-22 shows the configuration parameters and values used to create the multipath fault injection dataset. A fault bias of 36.8m was injected into the original pseudo-range of a single high elevation (G03) satellite from t=110s (SOW: 296228s) to t = 410s (SOW: 296528s), with an amplitude of 5m.

Table 6-22 TS15 Configuration

Parameter	**Value**	**Comment**
Start time [SOW]	[296228,];	represents the time and duration of the injection of the fault
End time [SOW]	[296528,];	
Constellation	['G'];	The constellation on which is affected
PRN	[3]	Satellites in which the fault was injected
Bias	[36.8]	fault bias values injected into the RINEX file.
Amplitude	[5]	Multipath components
Period	[30]	

6.1.7.1 TS13– PVTI Performance Analysis

Figure 6-39 and Figure 6-40 show fault detection test results from Test Scenario 13 EGNOS disabled. Figure 6-39 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the “red light” integrity alarm/flag is raised. Figure 6-40, shows integrity flags and the horizontal errors within the solution generated.

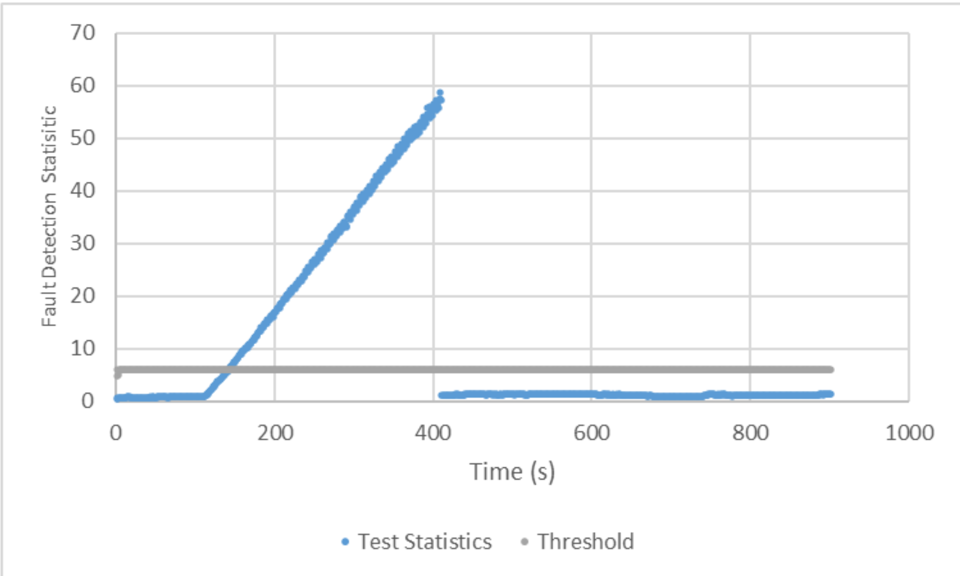


Figure 6-39 FD results from MGRAIM in Ephemeris fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 142s where $t^2 = 6.30 > T^2 = 5.94$ and ended at time 410s where $t^2 = 43.23 > T^2 = 5.94$. The horizontal error values at these times are 4.53m and 43.23m respectively.

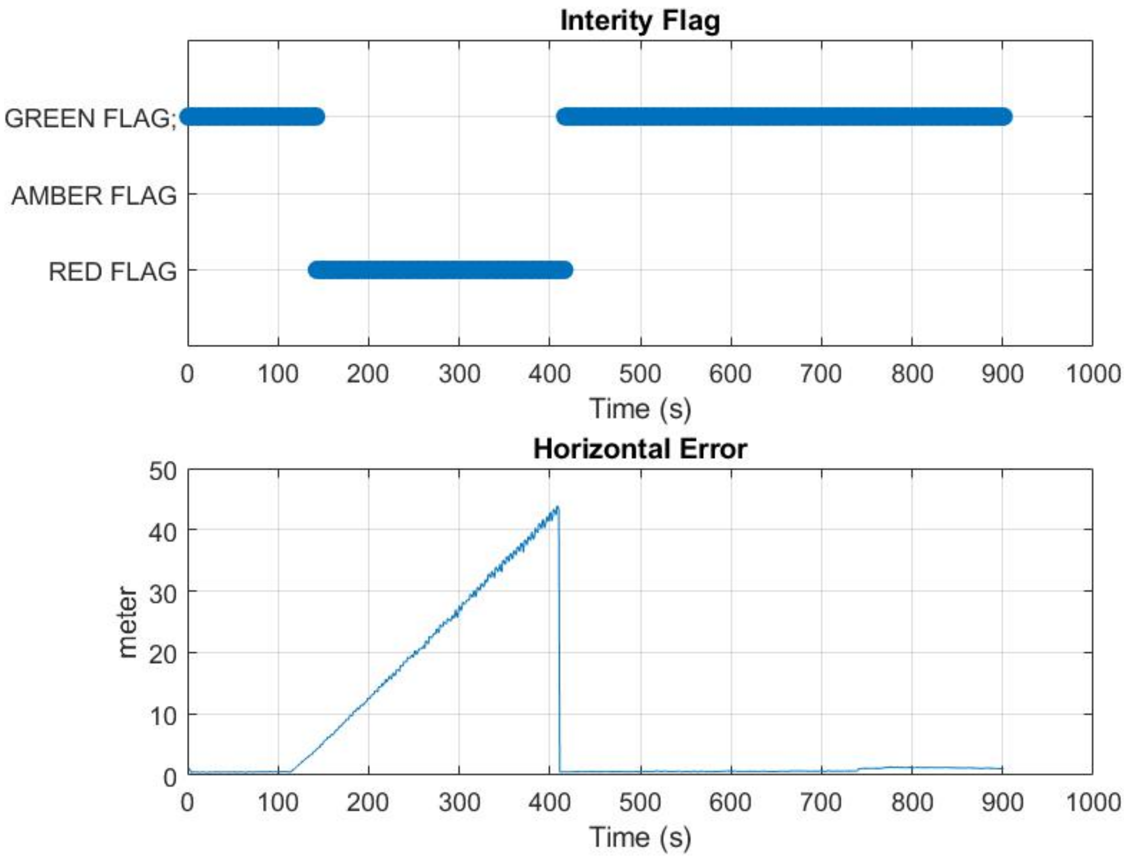


Figure 6-40 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-5. For GPS L1 the horizontal error is 36.635m with a percentile of 95%.

Table 6-23 TS04a - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-5.57	8.963	27.147
East	-4.386	8.738	25.027
Up	-19.388	33.425	98.637
Horizontal	7.634	12.193	36.635

Figure 6-41 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

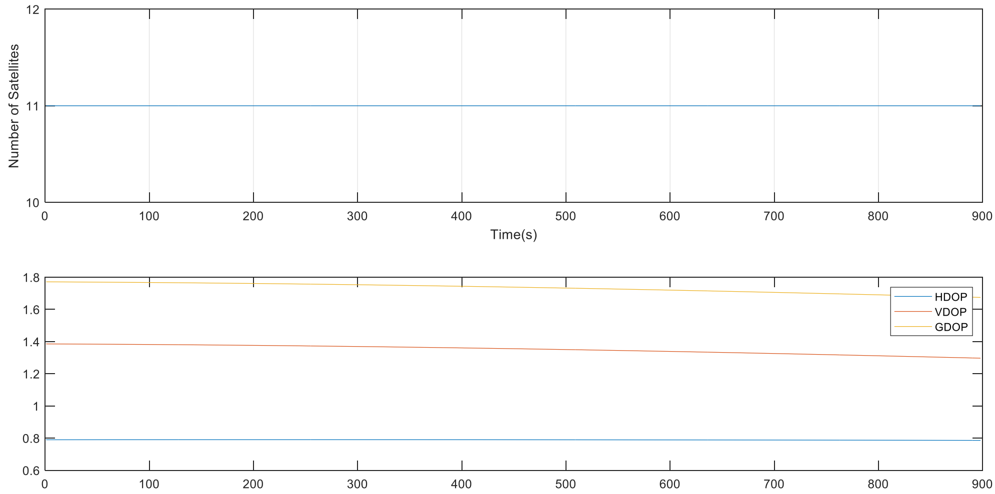


Figure 6-41 Number of SV used to generate the PVT solution and the DOP Values

6.1.8 Evaluation of a Multipath Error on a single Low-elevation SV

Table 6-24 shows the configuration parameters and values used to create the multipath fault injection dataset. A fault bias of 36.8m was injected into the original pseudo range of a single low elevation (G12) satellite from t=110s (SOW: 296228s) to t = 410s (SOW: 296528s) with an amplitude of 5m.

Table 6-24 TS14 Configuration

Parameter	Value	Comment
Start time [SOW]	[296228,];	represents the time and duration of the injection of the fault
End time [SOW]	[296528,];	
Constellation	['G'];	The constellation on which is affected
PRN	[3] [	Satellites in which the fault was injected
Bias	[36.8]	fault bias values injected into the RINEX file.
Amplitude	[5]	Multipath components
Period	[30]	

6.1.8.1 TS14 – PVTI Performance Analysis

Figure 6-42 and Figure 6-43 show fault detection test results from Test Scenario 14EGNOS disabled. Figure 6-42 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the “red light” integrity alarm/flag is raised. Figure 6-43, shows integrity flags and the horizontal errors within the solution generated.

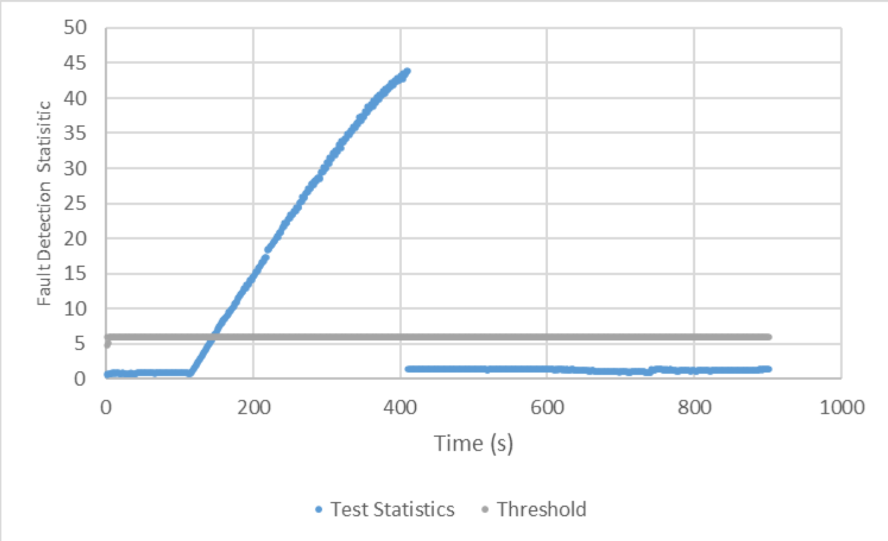


Figure 6-42 FD results from MGRAIM in Ephemeris fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 145s where $t^2 = 5.95 > T^2 = 5.94$ and ended at time 410s where $t^2 = 43.83 > T^2 = 5.94$. The horizontal error values at these times are 2.74m and 16.02m respectively.

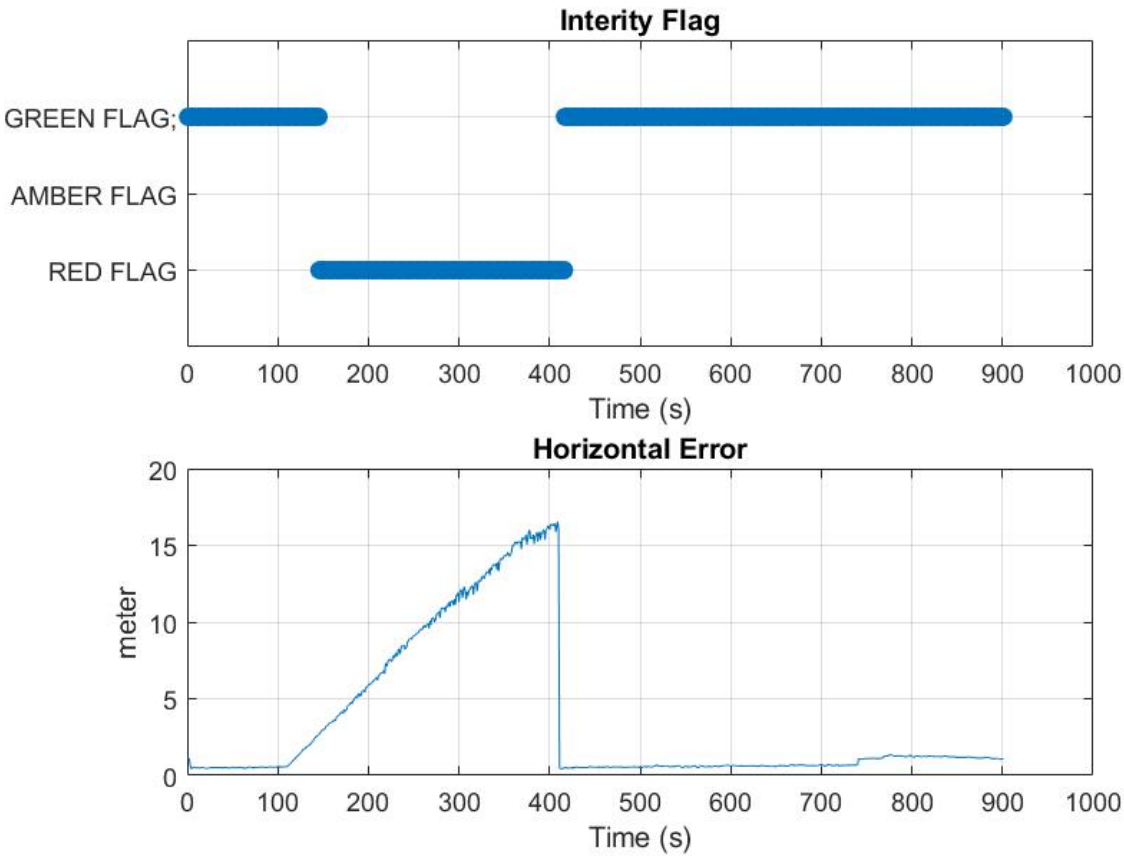


Figure 6-43 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-25. For GPS L1 the horizontal error is 15.133 with a percentile of 95%.

Table 6-25 TS14 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-2.761	4.062	12.26
East	2.164	2.718	8.733
Up	6.429	11.131	31.847
Horizontal	3.558	4.852	15.133

6.1.9 Evaluation of an Ionosphere Error on a single High-elevation SV

One of the largest errors in GPS positioning is attributable to the atmosphere. Through both refraction and diffraction, the atmosphere alters the apparent speed and, to a lesser extent, the direction of the signal. This causes an apparent delay in the signal's transit from the satellite to the receiver. The ionospheric delay varies with solar activity, time of year, season, time of day and location. This makes it very difficult to predict how much ionospheric delay is impacting the calculated position. The radio frequency of the signal passing through the ionosphere also varie with the ionospheric delay. Dual Frequency receiver can by comparing the measurements for L1 to the measurements for L2 determine the amount of ionospheric delay and remove this error from the calculated position. However, for single frequency receiver ionospheric models (e.g. Klobuchar Ionospheric Model and NeQuick Ionospheric Model) are used to reduce ionospheric delay errors.

This subsection shows the results generated using a smoothing constant of 100 seconds based on the following test scenario:

Test Scenario	*Correction mode*	*EGNOS mode*	*Fault injection*
TS.15	EGNOS disabled	N/A	Applying Ionospheric delay on a single high-elevation SV
TS.16	EGNOS enabled	Legacy (GPS L1)	Applying Ionospheric delay on a single low - elevation SV

Table 6-26 shows the configuration parameters and values used to create the Ionospheric fault injection dataset. A fault bias of 36.8m and drift of 0.4m/s was injected into the original pseudo range of a single high elevation (G03) satellite from t=110s (SOW: 296228s) to t = 410s (SOW: 296528s).

Table 6-26 TS15/TS16 Configuration

Parameter	*Value*	*Comment*
Start time [SOW]	[296228,];	represents the time and duration of the injection of the fault
End time [SOW]	[296528,];	
Constellation	['G'];	The constellation on which is affected
PRN	[3] [	Satellites in which the fault was injected
Bias	[36.8]	fault bias values injected into the RINEX file.
Drift	[0.4]	

6.1.9.1 TS15 – PVTI Performance Analysis (EGNOS Disabled)

Figure 6-44 and Figure 6-45 show fault detection test results from Test Scenario 15 EGNOS disabled. Figure 6-44 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the "red light" integrity alarm/flag is raised. Figure 6-45, shows integrity flags and the horizontal errors within the solution generated.

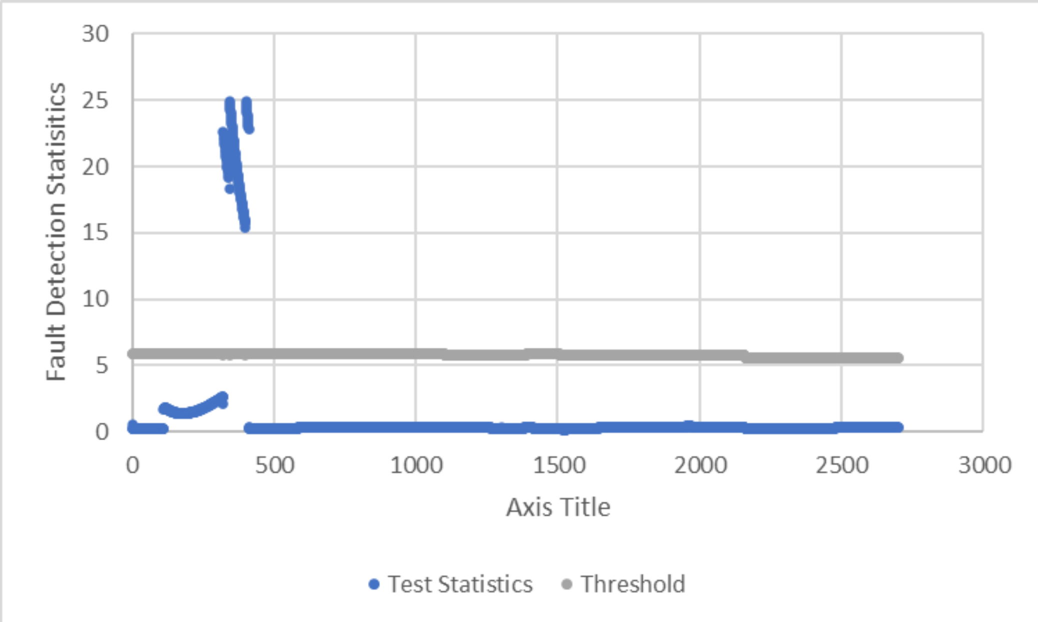


Figure 6-44 FD results from MGRAIM in Ephemeris fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 320s where $t^2 = 22.63 > T^2 = 5.94$ and ended at time 410s where $t^2 = 22.85 > T^2 = 5.94$. The horizontal error values at these times are 26.80m and 19.96m respectively.

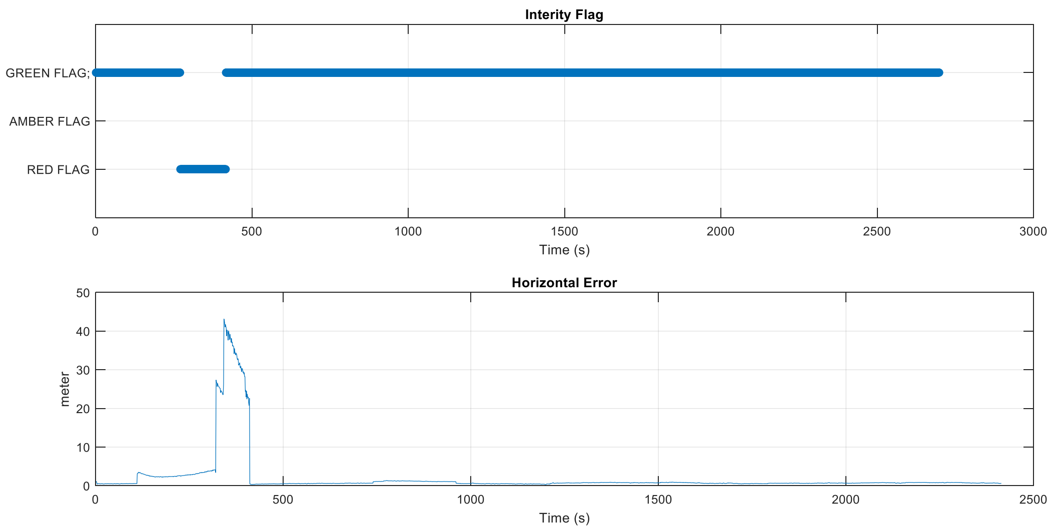


Figure 6-45 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-27. For GPS L1 the horizontal error is 4.29m with a percentile of 95%.

Table 6-27 TS15 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-2.041	5.516	3.931
East	0.425	2.032	1.269
Up	12.952	44.711	89.782
Horizontal	2.467	5.728	4.293

Figure 6-46 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

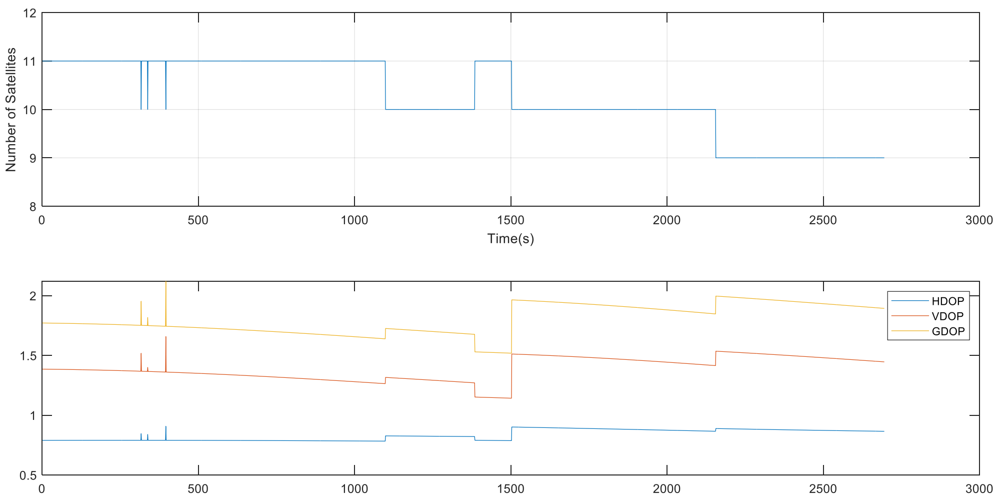


Figure 6-46 Number of SV used to generate the PVT solution and the DOP Values

6.1.9.2 TS16 – PVTI Performance Analysis (EGNOS Enabled)

Figure 6-47 and Figure 6-48 show fault detection test results from Test Scenario 16 EGNOS enabled. Figure 6-47 illustrates test statistics and threshold values computed for the solution generated for the dataset. The test statistics and threshold values are used within Fault Detection Test. It can be seen from the graph the point at which the test statistic exceeds the detection threshold, when this occurs the “red light” integrity alarm/flag is raised. Figure 6-48 shows integrity flags and the horizontal errors within the solution generated.

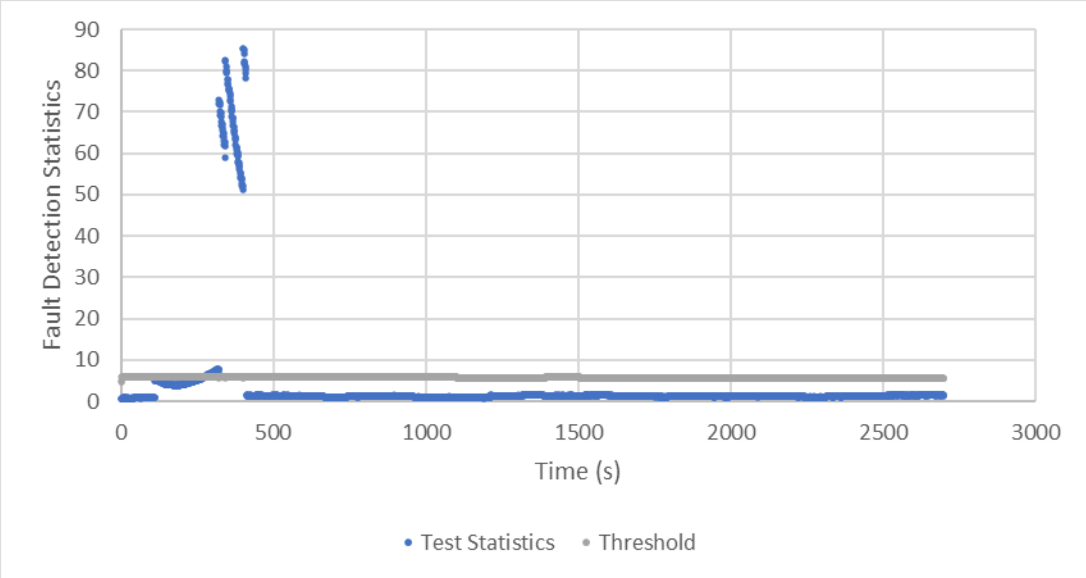


Figure 6-47 FD results from MGRAIM in Ephemeris fault case

The results indicate that the algorithm has detected the injected fault, as the RED flag is raised, this occurs when the test statistic exceeds the detection threshold ($t^2 > T^2$). The red flag was raised at time 273s where $t^2 = 5.96 > T^2 = 5.94$ and ended at time 410s where $t^2 = 78.20 > T^2 = 5.94$. The horizontal error values at these times are 3.14m and 22.6m respectively.

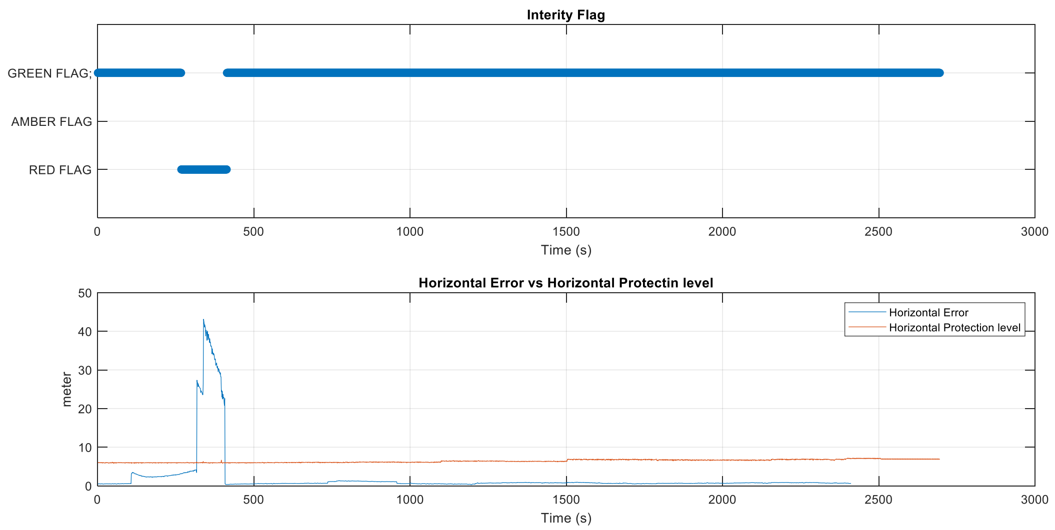


Figure 6-48 The MGRAIM Integrity Flag (above) and Horizontal Error vs HPL (below)

The solution performance is summarised in Table 6-28. For GPS L1 the horizontal error is 3.48m with a percentile of 95%.

Table 6-28 TS16 - NEU and Horizontal error parameters for GPS L1

	MEAN (m)	STD (m)	95% (m)
North	-1.396	5.755	3.386
East	0.392	1.957	1.195
Up	14.25	45.858	92.074
Horizontal	2.036	5.907	3.483

Figure 6-46 illustrate the number of satellites used to compute the PVT solution and the computed DOP.

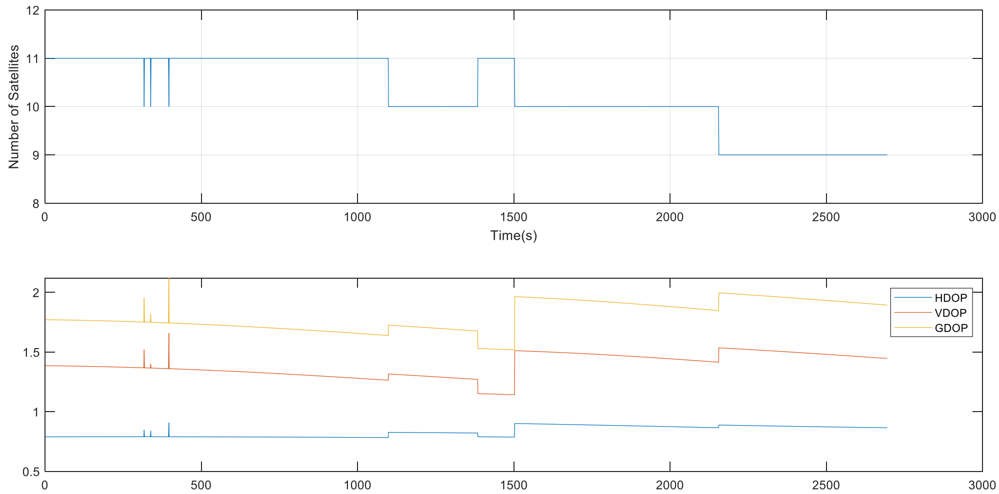


Figure 6-49 Number of SV used to generate the PVT solution and the DOP Values

6.2 Summary

The section looked at the PVT solution generated using the algorithm designed described in Section 4, which focused on fault detection. The functional testing and performance evaluation was executed based on the collection of real GNSS data (GPS and Galileo observables), using GMV facilities, in Nottingham. To evaluate the algorithm's ability to detect faults simulated data was used where the faults were injected into the RINEX file. The simulated data provided an option to cover scenarios that would otherwise not be possible using field data alone.

The results presented are for faults applied on a single satellite and have shown the that the algorithm is able to compute a PVT solution using the MGRAIM concept and when enabled using EGNOS (Legacy) for GPS single frequency data. It's been observed that the algorithm is able to detect the fault and raise the appropriate integrity status flag as defined in Table 4-2.

As the project progress future work will investigate further development of the MGRAIM concept, dual frequency data and faults that will affect multiple constellations.

7 ASSESSMENT OF NEED FOR MARITIME SPECIFIC SBAS MESSAGE

Integrity concept is understood as the ability of the system to provide timely warnings to users when the system should not be used for navigation.

In general, there are two different integrity concept levels: system level integrity, where some fixed infrastructure monitors the GNSS satellites to identify potential faults and disseminates alerts to user receivers, and user level integrity, where the user receiver itself checks the GNSS signals to detect faults considering the surrounding environment.

This section aims to explain the SBAS maritime system integrity provision, focusing on the expected development and detailing current SBAS status to analyse the need for a maritime specific EGNOS message.

7.1 SBAS Adoption

Mariners are already getting benefit from SBAS signal in space SiS in terms of accuracy. Currently a significant number of maritime non-SOLAS GPS receiver models in the market are SBAS-enabled[8].

Although the implementation of SBAS in maritime receivers is not yet standardised, 90% of manufacturers are offering at least 1 receiver model among their products that is SBAS-enabled. Most of the SBAS-enabled receivers integrate a DGNSS Rx with a SBAS-enabled Rx taking benefit from IEC-61108-1 [RD.40] and IEC-61108-4, which explicitly states that SBAS can be integrated to increase the resiliency of the PNT solution provided if the performances are not degraded; some manufacturers add RAIM on top of SBAS providing another source of integrity.

There has been more than a decade since IALA developed a World Wide Radio Navigation Plan (WWRNP) [RD.43] aimed at providing the WWRNS to support e-Navigation. One key WWRNP component to increase the resiliency of the PNT solution are the Satellite based Augmentation Systems, notably EGNOS in Europe. Since EGNOS is the system that is taking the initiative for SBAS penetration in the maritime domain, following chapters will detail the expected EGNOS adoption plan.

8 https://egnos-user-support.essp-sas.eu/new_egnos_ops/sites/default/files/workshop2016/01.%20GSA+ESSP%20-%20EGNOS%20Multimodal%20Adoption%20Plan%202016.pdf

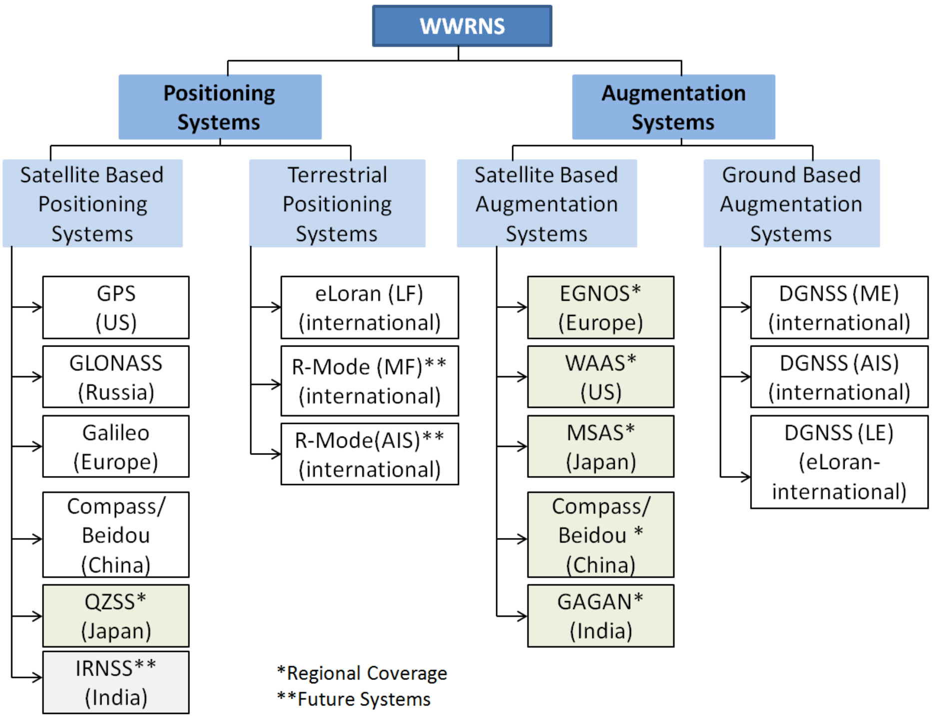


Figure 7-1: IALA's World Wide Radio Navigation Plan [RD.43]

SBAS/EGNOS are today widely adopted in leisure vessels as they can provide improved accuracy at no extra cost

Under the lead of EC, GSA, and ESA with the maritime/inland authorities and ESSP support it is currently in progress the work for the development of the EGNOS Maritime Safety services. The strategy for the use of EGNOS in the maritime domain is based on a three-step approach as depicted in the figure below:

- Transmission of EGNOS corrections (from SiS or EDAS) through the existing maritime shore infrastructure (AIS/VDES or IALA DGPS beacons)
- The use of EGNOS v2 Signal in Space directly.
- The use of EGNOS v3 (the next version of the system) Signal in Space.

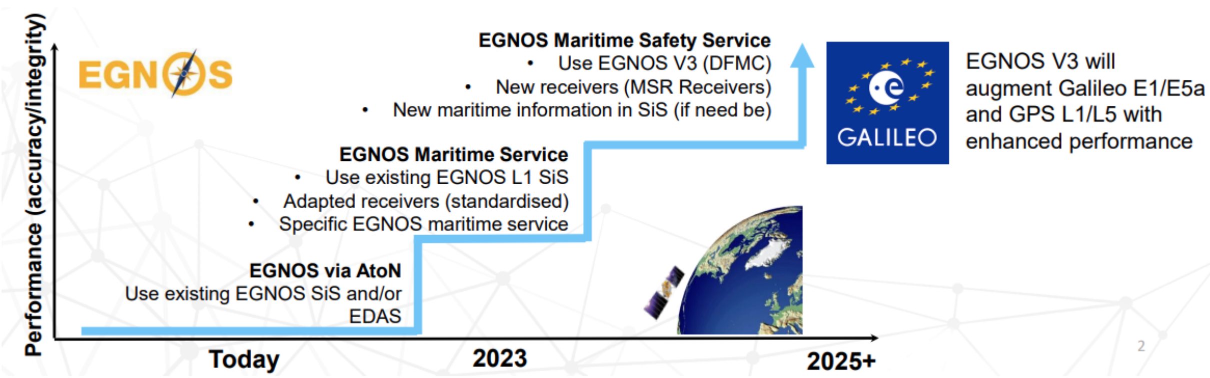


Figure 7-2 High-level Roadmap for EGNOS use in maritime [RD.44]

It is important to note that step 2 (Maritime Safety Service) is not dependent on step 1 (EGNOS via AtoN). EGNOS SiS at the vessel's receiver is considered the principal way in which the greatest number of maritime users will gain the most benefit from EGNOS V2. Step 1 is being considered by some Maritime Authorities in Europe to use EGNOS V2 through AtoN when a cost-effective architecture is identified.

7.1.1 EGNOS Open Service (OS)

As introduced, the current introduction of EGNOS in the maritime domain, even in the regulated sector, is constrained to the use of EGNOS Open Service (OS), as the adequate Service provision Scheme needed for the provision of EGNOS for the safety of maritime navigation (EGNOS Safety of Life Service - SoL) has not been put in place yet. In addition, specific implementation of EGNOS in the different maritime receivers is usually unknown, as there is not a SBAS/EGNOS standard for maritime applications.

According to the GNSS Market Report, Issue 4, March 2015, [RD.12] more than 75% of the GNSS receivers in the Maritime Segment were equipped with SBAS capability. Although that figure is not available in the more recent Market Reports, is expected to be growing in the recent years.

7.1.2 SBAS via IALA beacons

In line with the above strategy, the roadmap of the EGNOS V2 Maritime Service/Service Level compliant with the performance requirements in IMO Resolution A.1046 has been defined by EC and GSA in collaboration with ESSP and relevant maritime stakeholders.

Covering the activities for the first step, the roadmap elaboration has considered the main inputs and consensus from the European maritime community through the EMRF- (EGNOS) Service Provision Working Group (SPWG).
The different activities to declare an EGNOS V2 maritime service by the beginning of 2023 are currently running in parallel covering the following aspects:

1. IMO WWRNS Recognition
    a. MSC 98th (June 2017) concluded that there is no need to follow a process of recognition for EGNOS/SBAS once the Core constellations are recognized, which is the case of GPS and Galileo. EGNOS v3 will also augment Galileo which is also part of the WWRNS.
2. EGNOS Service Provision aspects
    a. Requirements under consolidation at the EMRF –Service Provision Working Group
    b. The high-level service provision scheme currently being proposed within the SPWG for EGNOS SiS maritime safety service is schematically shown below.

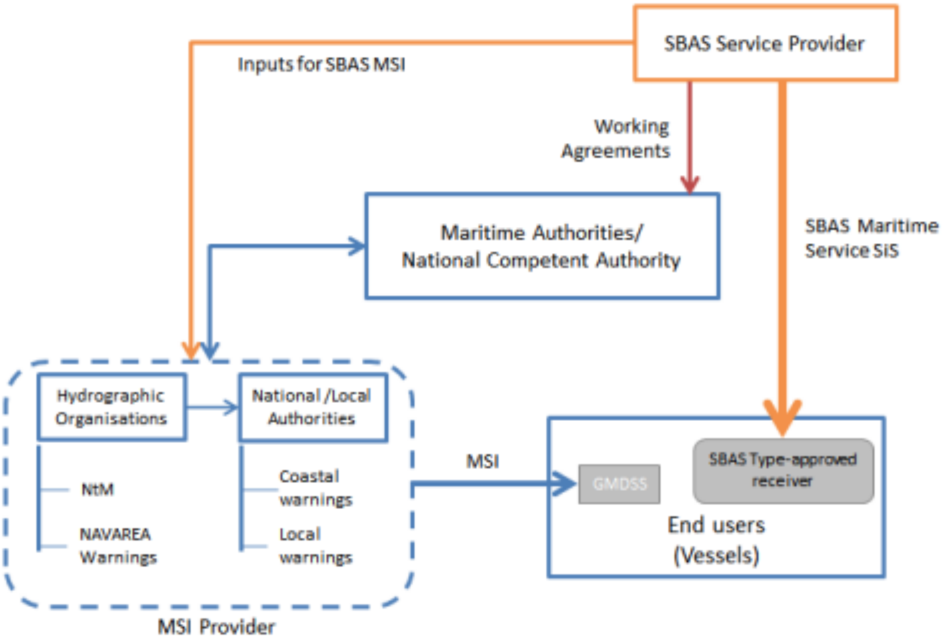


Figure 7-3: Service provision scheme [RD.45]

1. Standardization – SBAS RX Guidelines

- A working scheme is currently being developed through RTCM Special Committees (SC). Relevant SC's related to EGNOS V2 via AtoN is:
  - RTCM- SC 104: Develops standards for Differential GNSS (EGNOS V2 via AtoN) which are the de-facto standard for transmission of differential corrections over IALA Beacons:
    - RTCM 10402.3 RTCM Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) Service, Version 2.3. This standard is used around the world for differential satellite navigation systems, both maritime and terrestrial.
    - RTCM 10403.3 Differential GNSS (Global Navigation Satellite Systems) Services - Version 3 - A more efficient alternative to RTCM 10402.3
    - RTCM 10410.1, Standard for Networked Transport of RTCM via Internet Protocol (Ntrip) - An application-level protocol that supports streaming Global Navigation Satellite System (GNSS) data over the Internet.
    - RTCM 10401.2, Standard for Differential NAVSTAR GPS Reference Stations and Integrity Monitors (RSIM) - A companion to RTCM 10402.3, this standard addresses the performance requirements for the equipment which broadcasts DGNSS corrections.
  - The Draft Guidelines for Manufacturers for the Implementation of SBAS in Shipborne Receivers SBAS have been submitted to RTCM SC104 to be considered for the development of the SBAS receiver specifications.

2. Standardization – Multisystem RX including SBAS.
IMO MSC.401 (95) Resolution has established (NCSR 2 on 9-13 March 2015) [RD.4] the performance standards for multi-system - including augmentation systems - shipborne radio navigation receivers. The IEC performance requirements and tests specifications are the next step with fully approved receiver hardware expected to be available 2019/2020 at the earliest.

- RTCM:

- RTCM-SC 131: Issues standards for Multi-System Shipborne Navigation Receivers.
- To complement IMO Res. MSC.401 (95), RTCM SC-131 is already drafting the performance requirements and test specifications for the multisystem shipborne radionavigation receiver.

The work developed in RTCM SC-104 for the Draft Guidelines for manufacturers for the implementation of SBAS in shipborne receivers will be considered as an input for the development of the multisystem receiver test specifications including SBAS, in the frame of RTCM SC-131. Liaison between SC-104 and SC-131 is already established with respect to these SBAS Guidelines. IEC TC 80: IEC TC 80 is expected to finalize the test specifications for the type of approval of the multisystem shipborne radionavigation receivers with the support of RTCM SC-131 by mid- 2019.

3. EGNOS V2 via AtoN (IALA Beacon, AIS/VDES)
The Guidelines for the maritime use of SBAS have been developed in the frame of IALA ENAV Committee, in WG5 which deals with PNT aspects. The objective of this document is to provide guidance to the different Maritime Administrations on the use and applications based on SBAS. This document contains a description of the SBAS, its uses and applications and how SBAS contributes to achieve a more resilient PNT in the maritime domain.
The main relevant IALA references for the guidelines development is:

- Recommendation A-124 APPENDIX 16 DGNSS Broadcasts from an AIS Service [RD.27]
- Recommendation R-135 on Future DGNSS [RD.28]
- Recommendation R-121 on Performance and Monitoring of DGNSS Services [RD.29]
- Guideline 1112 on Performance and Monitoring of DGNSS Services [RD.30]
- Guideline1060 – Recapitalisation of DGNSS [RD.31]
- Guidelines to Availability and Reliability to Aids to Navigation [RD.32]

This technology has demonstrated being the feasible of the different technical solutions based on EGNOS and its operational in some European countries.

Figure 7-4. EGNOS correction via DGNSS channel in maritime implementation status [RD.44]

7.1.3 EGNOS V2 Maritime Safety Service

In line with the above strategy, the roadmap of the EGNOS V2 Maritime Service/Service Level compliant with the performance requirements in IMO Resolution A.1046 has been defined by EC and GSA in collaboration with ESSP and relevant maritime stakeholders.

Covering the activities for second step, the approach considers developing this service using EGNOS SiS "as is" and hence the systems will be available according to the following key points [RD.44]:

- **Use current EGNOS L1 SiS**. EGNOS V2 Maritime Safety Service propose the use the current EGNOS L1 SiS "as it is" without any modification. Therefore, maritime community can exploit the benefits of the current developed solution for aviation making adaptation on top of the deployed system. This approach is extensive to the overall processing chain, which will be not modified for this EGNOS V2 Maritime Safety Service.
- **Adapted receivers**. To fulfil maritime regulation, it is required that SBAS receivers follows a recognized standard and apply for the wheel mark certification before its usage in SOLAS vessel. The IEC standardization process to produce a new standard IEC 61108-7 has already started. The title proposal is "Maritime navigation and radiocommunication equipment and systems - Global navigation satellite systems (GNSS) – Part 7: Satellite Based Augmentation Systems – Receiver Equipment – Performance requirements and method of testing".

  The New Work Item Proposal (NWIP) for maritime SBAS receiver was launched in February 2021 starting the international standardization process on the International Electrotechnical Commission Technical Committee (TC) 80. In June 2021, the NWIP was approved by the group and a new Project Team at IEC TC80 was created, PT61108-7, to work on the development of the standard for SBAS L1 maritime equipment. In November 2021 the first working draft, IEC 61108-7 WD, was presented at IEC TC80 with the aim of having the Committee Draft, IEC 61108-7 CD, in 2022. The standard IEC 61108-7 is expected to be completed by 2023.
- **EGNOS maritime service defined in the Service Definition Document (SDD)** including:
  - EGNOS L1 Signal-in-Space performance. based on analysis of 2 years of historical data of the EGNOS service, in particular statistics about the following error components will be provided
    - Satellite residual errors; including satellite positioning and clock errors
    - Iono residual error; considering the application of EGNOS ionospheric corrections. Please note that this limits the Service area to those monitored by EGNOS RIMS
    - Expected range error overbounding. An indication about the expected error coming from non-monitored sources (i.e., tropospheric, multipath, etc.) will be provided. Note that these overbounding models are just provided as an indication and mariners could implement any other
  - Alarms for error protection. Note that these alerts were designed for aviation community and therefore they are not specific for the maritime service.
  - Notification to mariners (NtM). The MSI provider is encouraged to promulgate to the users, using approved procedures, the MSI related to SBAS Maritime Service status and degradations. Depending on the specific characteristics of the SBAS MSI, the MSI provider will distribute the information as Navigational warnings (NAVAREA, coastal or local warnings) or Notices to Mariners (NtM).
  - Indicative values of the scaling factors to derive real UDRE and GIVE EGNOS computed values based on EGNOS historical performance.
  - Even if no commitment is taken on position domain performance, performance at user level (IMO 1046) will be assessed using representative error models for local environment (e.g., H2020 SEASOLAS and MARGOT studies). The objective is to show that EGNOS maritime service can support IMO 1046 applications.

As a summary, the EGNOS V2 Maritime Safety Service does:

- not make commitments on position domain performances
- not take responsibility for the user environment
- provide expected service performance at GNSS SiS level
- not change the current EGNOS system/signal

7.1.4 EGNOS V3 Maritime Safety Service

EGNOS V3 Safety Service for maritime and inland waterways will take full advantage of the MFMC (Multi-Frequency Multi-Constellation) benefits increasing the robustness of the application and the resilience of the PNT solution.

One of the key aspects to remark is that while the integrity parameters of IMO A.1046 [RD.25] only request integrity at System level, IMO A.915 [RD.24] requires integrity at user level as discussed in section 3.3.

On this basis the definition of a maritime GNSS integrity concept at user level (algorithms modelling the maritime environment, protection levels definition…) is fundamental. This definition will impact on relevant work streams dealing with:

- SBAS receiver standardisation

  The development of SBAS receiver standards, including new integrity concept (to be defined) should be addressed. The user requirements should be considered as an input for this development. Additional topics to be assessed are:

  - Maritime scenarios characterization and modelling (for user integrity provision)
  - Multi-constellation
  - Multifrequency
  - Multisystem receiver standardisation

- It would be necessary to evaluate if the multisystem standard [RD.26] will need to be updated to consider the new EGNOS system release specifications

It should also be noted that the maritime world is likely to change during this period, too. There is a general trend today for commercial vessels to become larger, with more integrated bridge systems and the IMO E-Navigation concept is working to make maritime transport safer, more environmentally friendly and cost efficient. Navigation will see greater system integration and more reliance on system integrity, i.e., reliability on the on-board Navigation system information, and the need for resilience in system information, specifically the vessels position, navigation and timing information. EGNOS V3 is likely to be in use on SOLAS and non-SOLAS vessels as part of the multi-system shipborne receiver (MSR) concept.

The Service Provision Scheme of the EGNOS V3 maritime safety service is being defined in several European initiatives, such as SEASOLAS project, considering as input the status of the EGNOS V2 service provision scheme. In particular, the following factors are being considered:

- Provision of integrity at user level is subject to the discussion detailed in section 3 regarding the existing integrity performance requirements and the understanding of integrity concept in maritime domain. It is expected, that by the time of the EGNOS V3 Safety Service deployment, by 2028 (see Figure 7-5), integrity requirement would be consolidated, and the needs of E-Navigation would clarify the frame of the the multi-system shipborne receiver (MSR).
- Harmonized service provision scheme for all EU countries including the appropriate tailoring of service and liability scheme.

- Sound and safe interfaces and procedures with the maritime authorities, hydrographic institutions (MSI) and RIS (NtS) stablished. This includes the promulgation of MSI.
- Backward compatibility with EGNOS V2 services.
- Interoperability with other SBAS to ensure seamless operation at sea and in rivers. The existing SBAS systems meet common standards and interoperability requirements. Therefore, they are all compatible (do not interfere with each other) and interoperable (a user with a standard receiver can benefit from the same minimum level of service and performances independently of the SBAS service areas)[9]. A relevant element for the mariner is that EGNOS V3 Safety Service should support all phases of the voyage, berth-to-berth and its associated e-Navigation services throughout a service area that covers all European waters.

It might take an average of 18 months to place a commercial receiver on the market after the approval of the MFMC Multi-system receiver standard; 6 months for the Notified Body to establish and prepare the test environment and test procedure; 1 year for the Receiver manufacturer to proof the product and get the certificate.

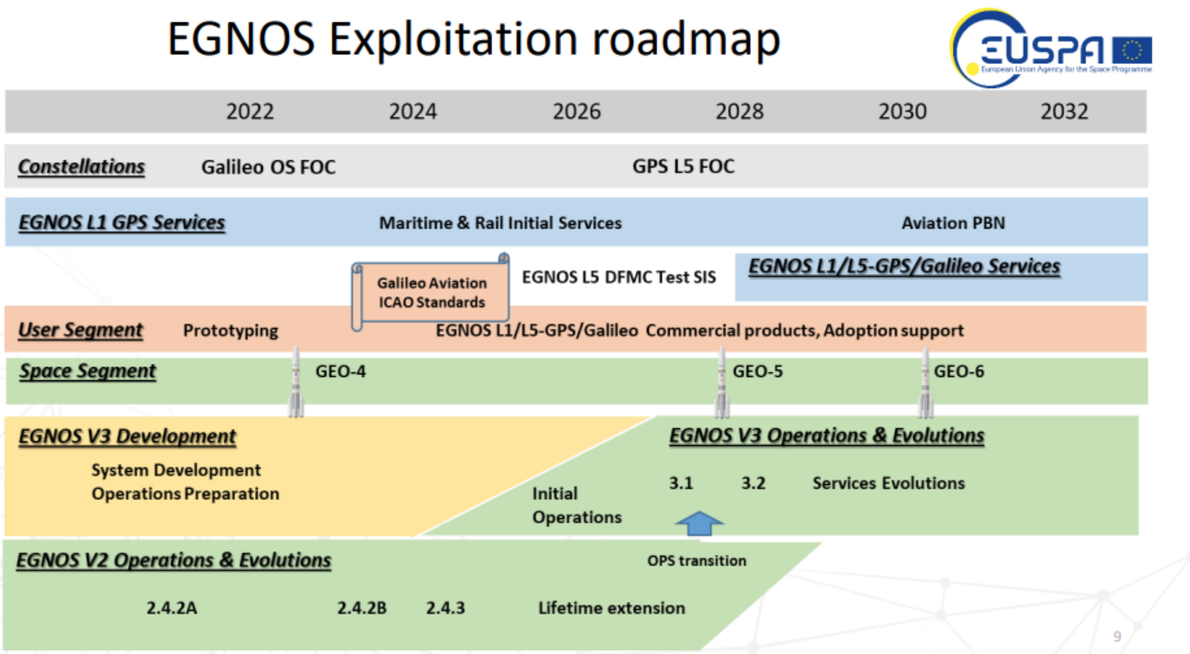


Figure 7-5. EUSPA EGNOS Exploitation roadmap [RD.44]

7.2 SBAS Architecture

The main elements of a basic SBAS architecture, and any space application, is divided in space, ground and user segment. Details of each of them are provided in the following sections.

9 The SBAS service providers of the different SBAS systems meet regularly at the Interoperability Working Group (IWG) to address the key aspects related to the harmonization of current and future plans in terms of certification, standardization, safety, operations and research and development. The WG-C on SBAS exploitation subgroup established between EC and FAA also addresses similar topics.

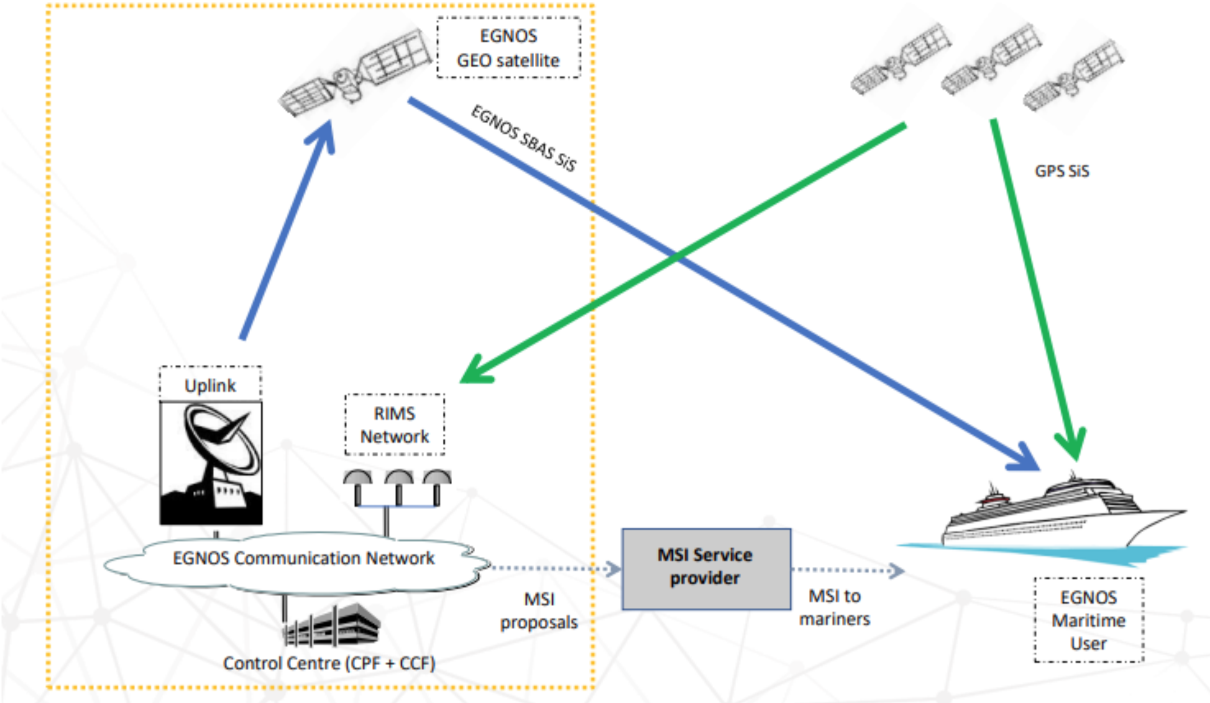


Figure 7-6. EGNOS Maritime Service Architecture [RD.45]

7.2.1 Space Segment

Includes the satellites with payloads aimed to transmit the corrections to the GNSS core constellations and integrity information. In case of EGNOS, Space segment is composed of four geostationary satellites (GEO) broadcasting corrections and integrity information for GPS satellites in the L1 frequency band (1575,42 MHz).

- Inmarsat 3F2 AOR-E | PRN Number 120 | Orbital Slot 15.5 W
- Astra Ses-5 | PRN Number 136 | Orbital Slot 5 E
- Inmarsat 4F2 Emea | PRN Number 126 | Orbital Slot 64 E
- Astra-5B | PRN Number 123 | Orbital Slot 31.5 E

On 1st January 2019 the INMARSAT 3F2 AOR-E (PRN 120) was decommissioned. From 23rd March 2020 onwards, PRN123 and PRN136 are operational while the PRN126 is in test mode.

7.2.2 Ground Segment

It comprises a network of Ranging Integrity Monitoring Stations (RIMS), two Mission Control Centres (MCC), two Navigation Land Earth Stations (NLES) per GEO satellite, and the EGNOS Wide Area Network (EWAN) which provides the communication network for all the components of the ground segment. Two additional facilities are also deployed as part of the ground segment to support system operations and service provision, namely the Performance Assessment and Checkout Facility (PACF) and the Application Specific Qualification Facility (ASQF), which are operated by the EGNOS Service Provider. Detailed description for the key elements are the following:

- **Monitoring Station Network**. The main function of the Ranging Integrity Monitoring Stations (RIMS) is to collect measurements from GPS satellites and to transmit these raw data every second to the Central Processing Facilities (CPF) of each MCC. The initial EGNOS configuration included 34 RIMS sites located over a wide geographical area.

- **Central Processing Facility**: is a module of the Mission Control Centres that uses the data received from the network of RIMS stations to:
  - Elaborate clock corrections for each GPS satellite in view of the network of RIMS stations. These corrections are valid throughout the geostationary broadcast area (i.e. wherever the EGNOS signal is received).
  - Elaborate ephemeris corrections to improve the accuracy of spacecraft orbital positions. In principle, these corrections are also valid throughout the geostationary broadcast area. However, due to the geographical distribution of the EGNOS ground monitoring network, the accuracy of these corrections will degrade when moving away from the core service area.
  - Elaborate a model for ionospheric induced delay over the EGNOS service area in order to compensate for ionospheric perturbations to the navigation signals.
  - Estimates the residual errors that can be expected by the users once they have applied the set of corrections broadcast by EGNOS. These residual errors are characterised by two parameters:
    - User Differential Range Error (UDRE): this is an estimate of the residual range error after the application of clock and ephemeris error correction for a given GPS satellite.
    - Grid Ionospheric Vertical Error (GIVE): this is an estimate of the vertical residual error after application of the ionospheric corrections for a given geographical grid point.
- **Satellite Control Centre:** These facilities ensure permanent service monitoring and control. In case of EGNOS, they are called Mission Control Centre and each of them host one CPF and one Central Control Facility (CCF). This last module is in charge of the monitoring and control of the entire EGNOS system. The main functions are:
  - Monitor and control all the EGNOS ground subsystems.
  - Monitor the system mission, the EGNOS satellites and predict the service performance.
  - Archives all collected and produced data.
  - Provide interface to PACF and ATC (Air Traffic Control).
- **Navigation Land Earth Stations (NLES):** These stations receive the EGNOS messages from all the CPFs for the upload of the data stream to the geostationary satellites and the generation of the GPS-like signal. For each of the three EGNOS geostationary satellites to upload, two dedicated NLES stations (one active and one as a hot backup) are deployed, for a total of six operational NLES stations, which are totally interchangeable.

7.2.3 User segment

Includes the user equipment needed to receive and use the SBAS information and accurately compute their positions with integrity. To receive SBAS signals, an SBAS compatible receiver is required; they are already available on the market from a variety of manufacturers.

An SBAS receiver is like a GPS receiver but with special software inside that allows the receiver to lock onto the code used by the SBAS satellites and compute the SBAS corrections to the GPS signals. An SBAS receiver is the same size as a GPS receiver and uses the same type of antenna.

7.3 SBAS System level integrity

As mentioned before, SBAS it is a wide coverage augmentation system in which the user receives augmentation information from a satellite-based transmitter. It is composed of a network of monitoring stations which collect GNSS data from constellations and then a processing facility analyses it to generate the corrections to the SIS data. This information is sent by a set of uplink stations to geostationary satellites which broadcast the corrections to the user.

Therefore, the SBAS integrity service should protect the user from both:

- Failures of GNSS/GEO satellites (drifting or biased pseudo ranges) by detecting and excluding faulty satellites through the measurement of GPS signals with the network of reference ground stations
- Transmission of erroneous or inaccurate differential corrections. These erroneous corrections may in turn be induced from either:
  - Undetected failures in the ground segment
  - Processing of reference data corrupted by the noise induced by the measurement and algorithmic process.

This last type of failure is the one that may occur when the system is in a nominal state (no GNSS/GEO satellite failure, no ground segment/user equipment failure) and it is usually known as "fault free case". This is the kind of error that is addressed by the User level integrity concepts detailed in section 3.2.3 and the difference between EGNOS V2 and V3 Maritime safety Services.

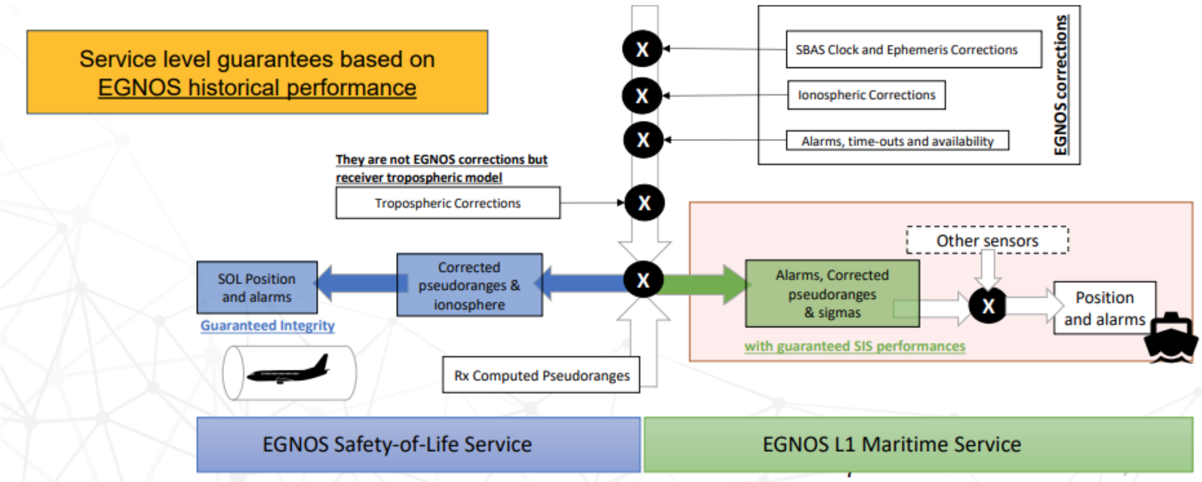


Figure 7-7. EGNOS V2 Maritime Safety Service integrity concept [RD.44]

In this former case, EGNOS system is designed to provide what in aviation is called ground system integrity. It is an equivalent concept to system level integrity and its risk allocation (10^{-7}/ per approach in case of APV and Cat I aviation operations) should cover:

- Failures on navigation code and data transmitted by GNSS satellites (including evil waveforms).
- Corruption of data to be transmitted to the user, through the geo satellites.
- Failures issued from the ground system hardware, software design or corruption of data through the Wide Area Network connecting the ground elements.
- Errors in the calculated model for ionospheric induced delay over the EGNOS service area.

This protection guarantees the SiS performance in terms of safety and would limit the integrity risk for maritime user only to those events that could corrupt the signal in the vessels surroundings. In addition, the integrity provided can be used for the fusion with information from additional sensors to provide the maritime position and alarms aligned with the current maritime concept of integrity.

7.4 SBAS Message architecture, need of Maritime message

7.4.1 Message architecture for EGNOS V2 Maritime Safety Service integrity provision

The content of this section has been compiled from Appendix A of RTCA DO-229E - Minimum Operational Performance Standards For Global Positioning System/Wide Area Augmentation System Airborne Equipment [RD.4], and adapted when necessary considering the modifications proposed in the Guidelines for Manufacturers for the Implementation of SBAS in Shipborne Receivers.

The EGNOS signal-in-space is broadcast by Geostationary Earth Orbit (GEO) satellites in the L1 frequency, centred at 1575.42 MHz, meeting stringent standards established by organizations like ICAO and RTCA.

The next evolution of EGNOS; namely EGNOS V3, will provide dual-frequency signals on both bands L1 and L5 augmenting both GPS and Galileo constellation data.

The basic SBAS SiS characteristics are:

- Frequency: 1575.42 MHz (L1)
- Polarization: RHCP
- Modulation: Bi-phase shift-keyed (BPSK) at of 1.023 Mchips per second.
- Data rate: 250 bit per second
- Format summary: All messages shall consist of:
  - Message type identifier
  - Preamble
  - Data field
  - Cyclic redundancy check

The broadcast signal is a combination of a 1023-bit PRN navigation code of the GNSS and a 250 bits per second navigation data message carrying the corrections and integrity data elaborated by the SBAS ground segment. The SBAS message's structure is schematically shown in Figure 7-8

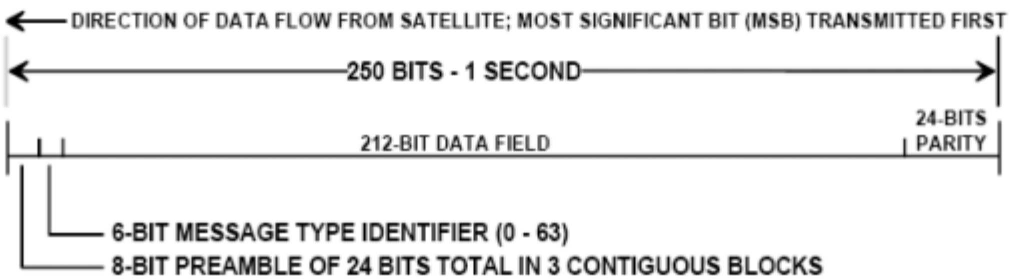


Figure 7-8. General SBAS L1 message structure[RD.4]

The content of each SBAS message type is summarized below:

Table 7-1. SBAS Messages Type

MT#	Type Contents	Purpose
0	Don't use for safety applications	Discard any ranging, corrections and integrity data from that PRN signal for safety applications.

MT#	Type Contents	Purpose
1	PRN mask assignments, set up to 51 of 210 possible	Indicates the slots for GPS and Augmentation satellites provided data
2-5	Fast corrections	Range corrections and accuracy
6	Integrity information	Accuracy-bounding information for all satellites in one message
7	Degradation Parameters	Information about the degradation of the fast term corrections
9	Geo Navigation message (*X*,*Y*,*Z*, time, etc.)	SBAS satellites orbit information (ephemeris)
10	Degradation parameters	Information about the correction degradation upon message loss
12	SBAS Network time / UTC offset parameters	Parameters for synchronisation of SBAS Network time with UTC
17	Geo satellite almanacs	Augmentation Satellite Almanacs
18	Ionospheric grid points masks	Indicates for which geographical point ionospheric correction data is provided
24	Mixed fast corrections/long term satellite error corrections	Fast-term error corrections for up to six satellites and long-term satellite error correction for one satellite in one message.
25	Long term satellite error corrections	Corrections for satellite ephemeris and clock errors for up to two satellites
26	Ionospheric delay corrections	Vertical delays/accuracy bounds at given geographical points
27	SBAS Service message	Determines the δUDRE factor applicable in the Service Area.
28	Clock Ephemeris Covariance Matrix message	Relative covariance matrix for clock and ephemeris errors. Used to specify the correction confidence as a function of the user location.
62	Internal test message	Reserved (Internal Test Message)
63	Null message	Filler message if no other message is available

These messages relationship is detailed in the following figure.

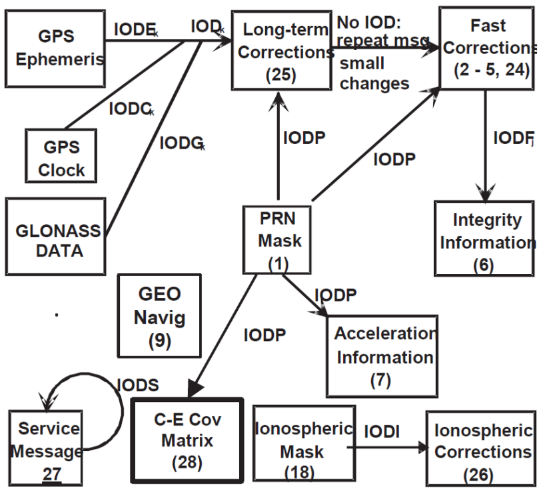


Figure 7-9. SBAS message relationship [RD.4]

As observed, these are the messages required for the integrity provision in aviation, and even for user level integrity not all of them would be mandatory. Integrity scheme detailed in section 7.3, for the second step of EGNOS adoption in maritime explained in section 7.1.3, does not require decode messages related directly with the computation of a positioning error bounding (Protection Level).

Should be considered that SBAS integrity information and error bounding's are valid only after corrections are applied. Therefore, all messages related with correction calculation and system level alarms should be decoded and processed.

In this case, to provide the system level integrity required the equipment should be able to process Message Types 0, 1, 2, 3, 4, 5, 6, 7, 18, 24, 25, 26 and 27 for accuracy and Integrity proposes. If GEO ranging is available, Message Type 9 and SBAS satellite almanacs provided in MT17, are recommended for tracking purposes and GEO elevation angle estimation. Additionally, the equipment optionally may process Message Types 10 and 28 for the estimation of standard deviation of satellite pseudorange residual error. Message Types that the equipment is not specifically designed to decode must be ignored.

Taking into account these mandatory messages to be decoded, the following system-related integrity information shall be processed by the receiver.

- **System alerts**: the receiver must not use corrections from that signal upon reception of Message Type 0.
- **Satellite alerts:** The equipment must decode the UDREI (UDRE Indicator) field of Message Types 2 to 5, 24, and 6 to determine if a failure of a specific satellite is indicated by the system. Every alert (UDREI = 15) condition will be repeated three times after the notification of the alert condition, that is, during an alert situation the message with the alarm information will be sent four times in four seconds, with the same information in all these epochs.

  In addition, satellite corrections are considered as valid to be used for maritime navigation solution when the satellite is monitored (UDREI≠14) and the UDREI indicate that performances are enough for the intended operation. Therefore, whenever a UDREI is received with value of, for example, 12 or greater, the GPS satellite to which that UDREI refers to shall not be used in the position solution computation until a different UDREI value is received.
- **Ionospheric alerts**: IGPs identified as "Don´t use" within Message Type 26 (IGPs with vertical delays of 63.875 m (111111111) corresponding with the field in Message Type 26) indicate an integrity risk detected by the system. After determining the location of the user ionospheric pierce point based on the IGP mask (Message Type 18), the user must select the IGPs to be used to

interpolate the ionospheric correction and model variance. If any of the selected IGPs is identified as “Do Not Use”, an ionospheric correction is not available. In that case, the SBAS ionospheric correction cannot be computed for that satellite. If four IGPs are selected, and one of the four is identified as “Not Monitored” (GIVEI=15), then three-point interpolation is used if the IPP is within the triangular region covered by the three corrections that are provided.

Decoding and processing of these three types of alerts, on top of the corrections provided and considering maybe a tropospheric error model, guarantees SiS integrity performances until the signal transmitted reach the user surroundings as explained in section 7.3. Therefore, further information that may be broadcasted by additional SBAS messages is not necessary. In addition, EGNOS system will not be modified for the EGNOS V2 Maritime Safety Service as explained in section 7.1.3.

7.4.2 Message architecture for EGNOS V3 Maritime Safety Service integrity provision

Additionally, the equipment optionally may process Message Types 10 and 28 for the estimation of standard deviation of satellite pseudorange residual error. Message Types that the equipment is not specifically designed to decode shall be ignored.

The following sections provide the current definition of the new SBAS L5 messages, broadcast on L5. The general format of the messages is nearly identical to the SBAS L1 message format as defined in section 7.4.1, except the preamble for which a new definition can be found, and the data field which is 4 bits larger. The basic SBAS SiS characteristics are:

- Frequency: 1176.45 MHz (L5)
- Polarization: RHCP
- Modulation: Bi-phase shift-keyed (BPSK) at of 10.23 Mchips per second.
- Data rate: 250 bit per second

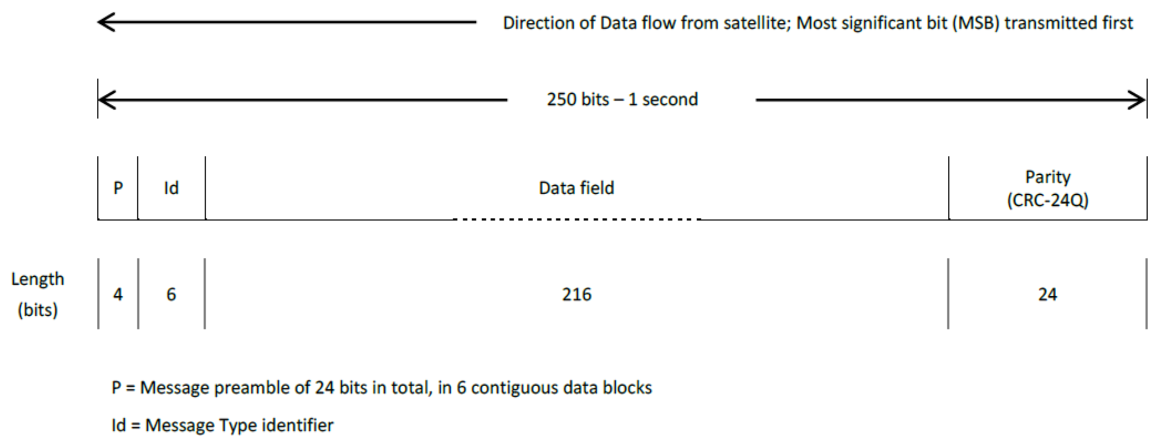


Figure 7-10. General SBAS L5 message structure[RD.47]

The SBAS L5 messages and their parameters are fully independent from the SBAS L1 messages and parameters and L1 messages will still be broadcasted by retro compatibility purposes.

L1 messages are intended for use with L1 SBAS service and L5 messages are intended for use with DFMC SBAS service. The messages on each frequency will be treated independently. Type 0, 62, and 63 messages act respectively for the frequency band on which they are broadcast.

Table 7-2. SBAS DFMC Messages Type[RD.47]

MT#	Type Contents	Purpose
0	Don't use L5 for safety applications	Discard any ranging, corrections and integrity data from that PRN signal for safety applications.
31	SBAS Satellite Mask assignments	It consists of 214 Satellite Slot Numbers, for which the associated Satellite Slot Value indicates whether correction and integrity data can be provided for the corresponding satellite
34, 35, 36	Integrity information (DFREI and DFRECI)	Transmit the Integrity information through DFRECIs and DFREIs, for all the Augmented Slot Indices derived from the SBAS Satellite Mask.
32	Satellite Clock-Ephemeris error corrections and covariance matrix	Provide error estimates for slow varying satellite ephemeris and clock errors. The MT 32 corrections and covariance matrix are estimated with respect to the GNSS broadcast clock and ephemeris parameters
39, 40	SBAS satellites ephemeris and covariance matrix	Contain the clock, ephemeris (transmitted as Keplerian parameters), and covariance matrix of the SBAS broadcasting satellite.
37	OBAD parameters and DFREI scale table	Contains the Old But Active Data (OBAD) parameters and the data which allow a given SBAS System to customize the $\sigma DFRE$ value for each DFRE Indicator
47	Almanacs of SBAS satellites	Contains the navigation data (as Keplerian parameters) describing the coarse position of two SBAS broadcasting satellites (for any type of orbit)
42	SBAS Network Time/UTC	Parameters for synchronisation of SBAS Network time with UTC
62	Internal test message	Reserved (Internal Test Message)
63	Null message	Filler message if no other message is available

In case system level integrity provision would be required, equivalent messages to MT#0 and MT#2 to 5, #24, and #6 are now MT#0, MT#34 to 36 and 37 respectively. In addition, any further information would be required to guarantee the SiS safety. Ionospheric information is not required in this case due to the use of double frequency processing that get rid of almost totally the error.

However, the intended EGNOS V3 Maritime Safety Service aims to provide user level integrity ant thus provide protection against "processing of reference data corrupted by the noise induced by the measurement and algorithmic process". In order to do so, the complete set of SBAS messages, both for L1 legacy and L5, needs to be decoded and processed.

Then, how to provide integrity depends on the implementation at user receiver. SBAS MOPS [RD.4] and [RD.47] provide in their annexes the process to be followed in order to compute a safe Protection Level. However, these procedures are tailored for aviation domain and, in case a PL concept is adopted by maritime and same rationale is selected, a deep adaptation would be required.

There are several initiatives for maritime such as the M-RAIM one proposed by MarRINav project [RD.38] and explained in section 3.5.1. This algorithm is based on the ARAIM concept, which make use of certain external information through the ISM. Although these parameters could be hardcoded, in order to optimise the performances, they may be disseminated by the GNSS satellites.

7.5 Preliminary Requirements for Maritime Specific EGNOS Message

As detailed in previous sections, for the proposed integrity algorithm there is no need for any additional SBAS message or even any modification to the already existing ones. However, this section details which would be the foreseen high-level requirements for a maritime specific SBAS message.

It is expected that any potential new SBAS message would be designed according to the following requirements, whose specific values have to be defined case by case.

- **Minimum affordable update rate**: Set a maximum time for message update. Some information might be refreshed often, like SBAS Fast Corrections, and some others could be updated in a much longer term
- **Message Time Out:** Set a maximum time for the message validity from its application time. Again, depending on the type of information the expiration time could be from few tens of seconds to several hours.
- **Bandwidth**: This requirement refers to the percentage of the new message bits in a given period of time. It is a combined requirement since it depend on the refreshment rate needed and also the length of the message. Please take into account that SBAS messages are limited to 250 bits including message header and tails, therefore if more information is needed more messages need to be sent. For example, SBAS ionospheric information change slowly but there are required few messages for the complete IGP map definition, and therefore few messages are required and higher bandwidth.

This section will be updated in future versions to take into account potential integrity algorithm upgrades.

End of Document