INSPIRe

D7.1 - GNSS DFMC Integrity Monitoring Report

R-062-001-017

Prepared for:

09 September 2023

1 TABLE OF CONTENTS

2 INTRODUCTION

2.1 Context and Objective

This report presents the conclusions of research into the concept and specification of an integrity monitoring system for dual frequency multi-constellation (DFMC) GNSS over the UK European Exclusive Economic Zone (UK EEZ) based on UK onshore monitoring assets only.

The project was conducted under WP7 of the INSPIRe Programme.

2.2 Contributors

CGI are the lead contributor for this project, having researched and developed the algorithms and architecture of the integrity monitoring system and identified the implementation programme.

GRAD has developed the dissemination function which is provided as an input to the integrity monitoring system.

Section 2.5 references the sections developed by CGI and GRAD.

2.3 Content

Section 3 presents the algorithmic model for a DFMC Service.

Section 4 outlines the architecture and high-level system design of a future DFMC System.

Section 5 establishes a Proof-of-Concept Testbed for candidate algorithms.

Section 6 reports the experimentation performed within the Proof-of-Concept Testbed.

Section 7 presents key elements of the remaining development and implementation programme required to create a DFMC Service.

Section 8 reviews the cost against similar undertakings.

Section 9 establishes traceability from the INSPIRe requirements to the proposed algorithmic processing model.

Section 10 provides the referenced sources.

2.4 Abbreviations

Abbreviation	Description
APCO	Antenna Phase Centre Offset
CDDIS	Crustal Dynamics Data Information System
DFMC	Dual Frequency Multi Constellation
DIM	DFMC Integrity Monitoring
EEZ	Exclusive Economic Zone
ETRF	European Terrestrial Reference Frame
EUREF	Regional Reference Frame Sub-Commission for Europe
GDOP	Geometric Dilution of Precision
GENS	GNSS Event Notification System
GGTO	GPS Galileo Time Offset
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GTRF	Galileo Terrestrial Reference Frame
HTTP	Hypertext Transfer Protocol
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
ICD	Interface Control Document
ICF	Integrity Check Function
IGS	International GNSS Service

IMS	Integrity Monitoring Station
IOD	Issue of Data
IODE	Issue of Data Ephemeris
ISB	Inter System Bias
ITRF	International Terrestrial Reference Frame
MCP	Maritime Connectivity Platform
MIR	Maritime Identity Registry
MMS	Maritime Messaging Service
MRAIM	Maritime Receiver Autonomous Integrity Monitoring
MSI	Maritime Safety Information
MSR	Maritime Service Registry
NTRIP	Networked Transport of RTCM via Internet Protocol
OS	Ordnance Survey
PKI	Public Key Infrastructure
PoC	Proof-of-Concept
PRN	Pseudorandom Noise
RTCM	Radio Technical Commission for Maritime Services
SBAS	Satellite Based Augmentation System
SISA	Galileo Signal in Space Accuracy
SISMA	Galileo Signal in Space Monitored Accuracy
SPAN	Southern Positioning Augmentation Network
UDRE	User Differential Range Error
UK EEZ	United Kingdom European Exclusive Economic Zone
URA	GPS User Range Accuracy
VDES	VHF Data Exchange System
VHF	Very High Frequency
VPL	Vertical Protection Limit
WAAS	Wide Area Augmentation System
WAN	Wide Area Network
WGS	World Geodetic System

2.5 Revision History

Revision	Author(s)	Date	Section(s)	Comments
V0.1	Peter Niemann CGI	2023-05-11	All	Draft for INSPIRe MTR
	GRAD	2023-02-15	4.1.4, 4.3.5, 4.4.3 7.1.5, 7.2.3, 7.3.2	
V0.2	Peter Niemann CGI	2023-08-15	Section 8 (new) ESA RIDs: Sections 3.2.1, 3.2.5.1, 3.4.5.3, 4.2.1, 4.2.1, 4.2.2, 4.2.4, 4.2.4.1, 4.2.4.1, 4.3.1, 4.3.1, 4.3.2, 4.3.3, 4.3.4 (new), 4.4.1	Draft for CGI internal review, addressing MTR feedback
V1.0	Peter Niemann CGI	2023-08-20		Formal issue following CGI internal review
V1.1	Peter Niemann CGI	2023-09-09	New section 2.2	Update following INSPIRe consortium review

3 ALGORITHMIC MODEL

The DFMC Integrity Monitoring (DIM) Service shall provide system level integrity assurance for maritime DFMC users in the UK EEZ, that is operating dual frequency receivers in dual frequency mode. Users are expected to use the DIM information within their DFMC MRAIM user level position solution within a system of systems. The present analysis therefore concentrates on providing integrity assurance on those elements of GNSS broadcasts which will be utilised by DFMC maritime users, with particular focus on threats and feared events where system level detection may offer complementary elements to local user level detection. There is no DFMC SBAS service currently available in the UK EEZ, and the present study does not presuppose its availability. The research was conducted under WP7.1 of the INSPIRe Programme.

Section 3.1 explores the approach to integrity assurance which the DIM Service may provide to users in the UK EEZ.

Section 3.2 discusses the integrity concept underlying the DIM System, as well as inherent constraints. This includes the domain of monitoring, the concept of overbounding, the definition of false alarm and missed detection, the approach to inter-system bias, and the geographic and geometric dilution constraints impacting the DIM System.

Section 3.3 analyses the threats and feared events which need to be detected and mitigated by the DIM System. This covers the threats applicable to the user but also threats inherent in the integrity monitoring system itself.

Section 3.4 develops a processing model to address the considerations and results of the earlier analysis.

Section 3.5 extrapolates the anticipated levels of performance which will be subject to experimentation in section 6.

3.1 DIM Service Concept

[INS Req] requirement [A0010] defines the INSPIRe integrity service as “The ability to provide users with warnings within a specified time when the system should not be used for navigation due to detected faults or an inability to detect faulted conditions.”

For a central integrity monitoring system, this requirement cannot be taken to mandate the provision of a single global GNSS integrity status because – to highlight just one issue – there will always exist GNSS satellites visible to some users in UK EEZ but not observable by UK onshore assets. As a result, there will always exist fault conditions which cannot currently be monitored by the central integrity monitoring system, necessitating a permanent global GNSS ‘not monitored’ status. Requirement [A0010] must therefore be understood to provide warnings with a greater level of granularity on appropriately selected elements of the overall GNSS information.

The DIM Service is an Integrity service only. In particular, no augmentation of the GNSS navigation information will be generated or distributed to users.

3.1.1 Monitored GNSS Elements

The information broadcast by GNSS satellites falls into the following classes:

- Satellite ephemeris and clock
- Satellite health information
- Almanac
- Ionospheric model

- Constellation time offset

Primarily, the DIM Service must provide its users with an assurance of integrity of the ephemeris and clock information broadcast by each GNSS satellite. This integrity status will be per GNSS satellite and take three values:

- A Green light, or Monitored status, indicates that the DIM Service was able to assure and monitor the broadcast satellite ephemeris and clock information.
- An Amber light, or Not Monitored status, indicates that the DIM Service did not have sufficient data to confirm integrity, but no errors or faults were detected.
- A Red light, or Don't Use status, indicates the detection of a range error exceeding the applicable error bound, or other feared event relating to that satellite. The GNSS health indicators shall be taken into account.

The DIM Service is not intended to assure or monitor the almanac broadcasts because these are used for initial acquisition rather than actual positioning.

The DIM Service is not intended to assure or monitor the ionospheric model information broadcast by GNSS because the dual frequency user will calculate their own ionospheric correction. More generally, the DIM Service will not assure or monitor the propagation environment. Local effects and threats such as jamming or ionospheric scintillation cannot be monitored comprehensively from UK onshore assets, and their communication across UK EEZ would require much greater bandwidth.

The DIM Service is not intended to assure or monitor the inter constellation time offsets such as the GPS Galileo Time Offset (GGTO). For positioning and navigation, the user receiver will need to model its hardware specific Inter System Bias (ISB), as elaborated in section 3.2.1 below. Furthermore, the DIM Service requirements do not include precision timing. Therefore, information specifically about integrity of the broadcast GGTO is not expected to be beneficial to the DIM user.

When issuing an alert on a given GNSS satellite the DIM Service will not provide any indication of the nature of detected faults, nor augmentation information to correct a detected fault. The user's means of mitigation is the exclusion of the flagged satellite from the user's position solution.

3.1.2 DIM Service Scope

The user of a Green light, or Monitored status, requires clear understanding of the extent of the DIM Service integrity assurance in order to correctly utilise this assurance in their local positioning.

The DIM Service will operate for users within the UK EEZ only. It will evaluate the integrity status of any GNSS satellite for any such user viewing the GNSS satellite at elevation angle greater or equal 5 degrees. A different elevation threshold may be set at system level but inevitably a common minimum elevation will apply to all users of the operational DIM Service.

The DIM Service must provide assurance for several dual frequency ionosphere-free combinations which the user algorithm may employ. The supported set of ionosphere-free combinations is provisionally identified to consist of GPS L1-L5, Galileo E1-E5a and Galileo E1-E5b.

The DIM Service must provide assurance for all live ephemerides of a GNSS satellite.

The DIM Service models the maximum error of the satellite in the pseudorange domain experienced by users within the UK EEZ and confirms its overbounding by the broadcast error bound (URA in the case of GPS, SISA in the case of Galileo). That is, the DIM Service assures the projected satellite error (for the worst user location in UK EEZ) only and does not

constitute a global integrity service message. Section 3.2.3 below justifies the choice of pseudorange domain. Section 3.2.4 elaborates the overbounding concept.

The DIM Service integrity assurance for each GNSS satellite is relative to this satellite's constellation network time, not against a multi-constellation user-level time. The multi-constellation user must account for the fact that each constellation employs its own frame of reference and constellation network time. The user's combined multi-constellation time frame will depend on the weight of the instantaneous contributions made by each of the two constellations and cannot therefore be modelled at DIM Service level.

Whilst for maritime users the horizontal error component may be more significant than the vertical one in their position solution, the DIM Service's modelling in the pseudorange domain equally covers both horizontal and vertical components.

The DIM Service furthermore assures that the GNSS satellite was monitored for feared events as per [INS Thr], and none were detected. Requirement [A0040] implies that, for example, a GNSS onboard clock jump detection shall result in an alert even if the satellite's broadcast URA/SISA covers the true user pseudorange error both before and after the jump.

In the event of a single event, such as an on-board clock jump, the satellite alarm status shall be maintained for a short period of 12 seconds only. However, the re-convergence of the DIM System models for the affected satellite will cause the satellite to remain not monitored for several minutes, ensuring that user filters will also have refreshed before data from the affected satellite can be used again.

3.1.3 Integrity Dissemination

Dissemination, both in terms of the detailed integrity message structure, and in terms of communications links, is defined in sections 4.2.5, 4.3.5 and 4.4.3 below. Dissemination will contribute to the DIM Service time-to-alarm performance. Dissemination does not, however, contribute to any other performance indicators.

3.2 DIM Integrity Concept

This section elaborates key aspects of the Integrity concept underlying the DIM System.

3.2.1 GPS – Galileo Time Offset

Any navigation solution employing GNSS satellites of two constellations must account for the inter-system bias, ISB. The total ISB experienced by user will consist of three components:

$$ISB = ISB_{to} + ISB_{ref} + ISB_{hw}$$

Where ISB_{to} represents the time offset of the constellations' network times, ISB_{ref} the difference of co-ordinate reference frames, and ISB_{hw} the receiver hardware bias generated due to different signal structure.

For the GPS-Galileo multi-constellation user, ISB_{to} is the GPS-Galileo Time Offset (GGTO) which is typically steered to within 1 to 2m. The difference between the GPS WGS84 and Galileo GTRF reference frames is at centimetre level [NAV TRF], and therefore ISB_{ref} is not expected to become significant for the targeted protection level.

User receivers are not typically calibrated to account for the ISB_{hw}, which has been shown to exceed 10m for some receivers [Gioia 2015]. Any user positioning algorithm, including any MRAIM algorithm will therefore need to account for the hardware ISB. Whilst ISB_{to} and ISB_{hw} are separate phenomena they act on receiver measurements in exactly the same way. Both

will apply, in full, to all the receiver's Galileo measurements (taking GPS time as reference time). ISB_{hw} is receiver specific and a central system cannot provide or account for it. There appears then to exist no benefit to the receiver or the user navigation solution in knowing GGTO in isolation. The DIM Integrity concept therefore understands that the user MRAIM algorithm would not directly use the GGTO information broadcast by the Galileo satellites.

With UK onshore receivers, the DIM System will by necessity be limited to a partial view of the constellation, which furthermore may not be identical to the partial constellation seen by the user. The DIM Integrity system will therefore not be able to monitor constellation network time which represents the average of the entire constellation.

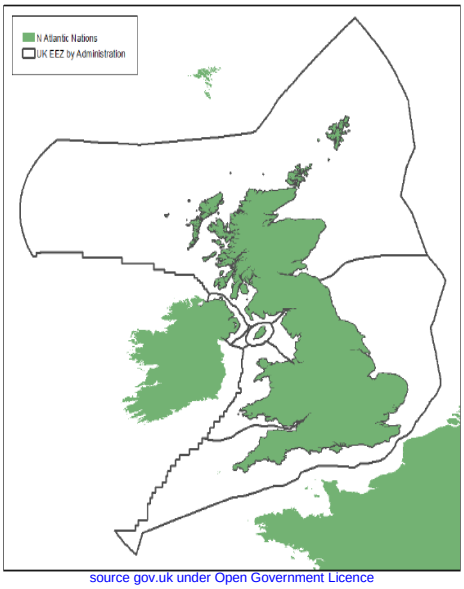
Considering both the partial visibility, and the user needs, the present study does not propose a DIM System module monitoring the time offsets between UTC, GPS network time and Galileo network time. A GGTO monitoring system could be constructed separately employing an independent high accuracy UTC time reference but would remain conceptually limited to the visible satellites.

We note that any instability, jump or ramp of GGTO which could indeed impact user positioning will by necessity be reflected in instabilities of one or more satellites of the affected constellation. The DIM System algorithms are designed to detect those instabilities.

The question how a user receiver manages the combined (ISB_{hw}+ ISB_{to}) element is outside the scope of the central system and the present study. To our knowledge, receiver behaviour is not standardised in this regard so that misinterpretation of DIM integrity assurances and incorrect xPL computations remain a significant risk. Standards for user computations have recently been developed in the context of future DFMC SBAS services.

3.2.2 GDOP

Figure 3-1 shows the geography the UK EEZ extending up to 212 nautical miles (400km) beyond the UK's shores.



source gov.uk under Open Government Licence

Figure 3-1 UK European Exclusive Economic Zone

The objective of the DIM System is to assure integrity throughout the UK EEZ relying exclusively on UK based assets. Measurement stations providing continuous measurements will therefore be constrained into a trapezoid of between 200km and 400km in East-West direction and 800km North-South. The narrow observation base results in geometric dilution because all line-of-sight vectors will be almost parallel in East-West direction. **Figure 3-2**

demonstrates the impact on the observability of a satellite at zenith with ephemeris error in East-West direction, almost orthogonal to the lines of sight. Elementary geometry confirms that as little as 1% of the actual error may be observable from UK shore-based assets.

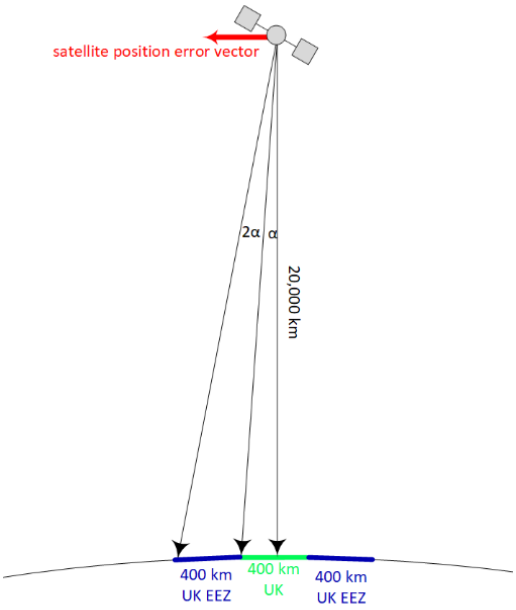


Figure 3-2 Satellite Position Error Projection (not to scale)

Continuing the simple geometric example, **Figure 3-2** demonstrates how users outside the geographic base, but within UK EEZ, may be able to observe three times the magnitude of error in the component orthogonal to monitoring lines of sight: Assuming perfect error free measurements, if the satellite position error projects to range error -ε in the West, and +ε in the East of the land mass, a mariner at the Western most point of UK EEZ will experience a range error of -3ε. At the same time, the monitored range errors average out at 0.

Conversely, the impact of the geometric dilution will artificially inflate the sample variance. In the example above, the two perfect measurements evaluate to a sample variance of $2\varepsilon^2$ when in fact they were perfect measurements, representing an overestimate of measurement noise.

The example highlights that any DIM error modelling must account for the inherent extrapolation in the modelling. At the same time, the narrow geographical base of the UK land mass creates significant challenges to residual error trend modelling such as via the construction of a residual error plane. Whilst this would deliver the correct answer in the example of **Figure 3-2** above, the narrow geographical base makes any extrapolation algorithm extremely vulnerable to small measurement errors, or error correlations. For example, if in **Figure 3-2**, the satellite position was accurate but the measurements subject to range errors +ε and -ε respectively, any attempt of fitting a trend would estimate an entirely spurious range error of 3ε for the worst user location. More generally, the inversion of measurement geometry, in whichever algorithmic realisation, will encounter near singular matrices, generating higher than acceptable false alarm rates.

The above examples of integrity performance constrain DIM algorithmic modelling. If a constant probability of missed detection is mandated throughout the UK EEZ, then the DIM System will require a form of extrapolation. This extrapolation will need to be chosen so that the detection capabilities meet the required false alarm and missed detection probabilities in the presence of geometric dilution of precision. Alternatively, the user integrity requirements for open seas may be reduced with respect to port navigation phases, with a gradually

increasing missed detection probability. Both approaches are developed in section 3.4.5.7 below.

The algorithm specification of section 3.4.5 and the PoC Experimentation of sections 6.2, 6.4 and especially 6.5.3 will further substantiate the impacts of GDOP on DIM Service performance. Whilst the scope of the current INSPIRe WP7 is firmly constrained to the use of UK based assets a future phase of INSPIRe may want to lift this constraint in return for greater algorithmic flexibility and performance.

3.2.3 Modelled Domain

Integrity modelling can a priori be performed either in the pseudorange domain, providing an assurance for the residual range error of each satellite, or in the user domain, assuring the error affecting the user position solution.

Many SBAS systems primarily model the pseudorange for their real time service broadcasts, with secondary tests performed by sampling the user domain [Walter 2017]. Position domain modelling contributes significantly to off-line performance assessment. Whilst the pseudorange domain model requires a critical mass and geographic distribution of receivers, the position domain model is evidently more scalable in that even a single receiver can generate some degree of integrity assurance.

[Walter 2017] however clearly identifies the limitations of a position domain approach in that the extrapolation to the worst case user is not theoretically well established. This argument acquires even greater significance for the present study considering the degree of extrapolation required to assure mariners in UK EEZ based on UK onshore receivers. Furthermore [Walter 2017] notes that a detected breach of position domain integrity would not readily identify and isolate the source of the fault. The system could only react with a global alert for all satellites involved in the computation, leading most likely to a complete loss of service.

Consequently, the present study does not consider modelling in the user position domain appropriate at this point and concludes that a pseudorange domain model will be necessary and sufficient to meet the study objectives.

3.2.4 Overbounding

Overbounding describes the precise statistical relationship in which a published error bound bounds the user error, in particular the tails of distribution. Several overbounding concepts exist. The fundamental difference between SBAS and Galileo integrity is that SBAS allows the user to compute a position error bound corresponding to a given p_{md}, whereas Galileo allows the user to compute an integrity risk corresponding to the alert limit, based on signal in space accuracy (SISA) and monitored accuracy (SISMA) [Hernandez 2009]. We note that SISMA is not currently broadcast by the Galileo service.

The maritime concept of overbounding is not presently established, and integrity could in principle be based on a variety of overbounding concepts. Considering that monitored accuracy is not currently available to the maritime DFMC user, and that the DIM Service will not provide additional UDRE or SISMA information, the study proposes to adopt the modified overbounding concept of [Mach 2006]. The projected GPS User Residual Error (URE) is overbounded, in the sense of [Mach 2006] by a Gaussian URA, and the projected Galileo signal in space error (SISE) is overbounded in the sense of [Mach 2006] by a Gaussian SISA, within the pseudorange domain. It is evident from section 3.2.2 above that the DIM Service can only assure overbounding for pseudorange errors projected to users within the

UK EEZ, not GNSS satellite ephemeris and clock error, which broadcast URA and SISA are designed to cover.

3.2.5 Missed Detection and False Alarm

The DIM Service will assure integrity subject to a false alarm rate derived from requirement [C0160]. This, in turn, requires a definition of an alarm condition at the satellite level against which missed detection and false alarm probabilities may be evaluated.

As per section 3.1.2 above, the DIM Service recognises and assures two types of alarm conditions: the presence of feared events at a GNSS satellite, and the breach of the error bound broadcast by the GNSS satellite.

3.2.5.1 Breach of GNSS Error Bound

Following the decision to monitor in the pseudorange domain, the alarm condition shall verify if the maximum residual error at the worst user location is consistent with the broadcast GPS URA and Galileo SISA values.

For an SBAS service, [NAV SBAS] derives the value of this maximum user error threshold from the definition of the user's vertical protection limit (VPL) in the user position domain. For the VPL, at an integrity assurance level of 1-(1e-7), the user will apply a factor of 5.33 to their computed 1σ error, corresponding to the tail of the cumulative distribution function. Any SBAS integrity monitoring system must then apply the same factor to the threshold within the pseudorange domain.

For the maritime service, the concept of a protection limit is not defined, so it is not guaranteed that all users will scale their error bounds, be they vertical or horizontal, in the same way or with the same goal of assurance. Section 6.2.1 of [SPS 2020] clarifies the significance of the GPS URA broadcast as that "*4.42 times URA bounds the instantaneous URE with 1-(1e-5) per hour probability*". There are no illustrative limits proposed in [OS SDD 2021] for Galileo SISA. Whilst greater standardisation of the maritime domain in this respect would be beneficial and proposed in the implementation plan, for the purposes of the experimentation under the current study, the threshold will be set for both URA and SISA through a k-factor $k_{maritime} = 4.42$. For clarity, we will refer to σ_{URA} and σ_{SISA} below.

As will be shown in section 6.5.3 below, the geographic footprint of UK based observations will not permit the safe separation of vertical and horizontal errors. The DIM System therefore considers missed detection and false alarm based on total error though we acknowledge that the horizontal error is clearly more significant than the vertical in the maritime domain.

A missed detection occurs if the DIM System raises no alarm but the true pseudorange error at worst user location exceeds $k_{maritime}\ \sigma_{URA}$ or $k_{maritime}\ \sigma_{SISA}$. The DIM Service requirements do not prescribe a numerical target for missed detection. Achievable levels will be experimented in section 6, starting from a provisional target of $p_{md} =$ 1e-3.

The definition of a false alarm naturally is the mirror of the above, that is that the DIM System raises an alarm even though the true pseudorange error at worst user location did not exceed $k_{maritime}\ \sigma_{URA}$ or $k_{maritime}\ \sigma_{SISA}$. The probability of false alarm for a given satellite can then be expressed as:

$$p_{fa} = p\,(Res_{Model} > Thr \quad \&\& \quad URE < Thr)$$
$$= \int_{x=0}^{\infty} p(Res_{Model} > Thr \mid Thr - URE = x)\, p(Thr - URE = x)\, dx$$

Where Res_{Model} represents the satellite residual error at worst user location modelled by the DIM System, Thr may equally stand for $k_{maritime}\,\sigma_{URA}$ or $k_{maritime}\,\sigma_{SISA}$, URE represents the true satellite residual error at worst user location. It is evident that no p_{fa} target can be achieved independent of the underlying distribution of errors. To illustrate, if a satellite's URE was consistently just fractionally below or above Thr, with half of epochs in breach, even under the most accurate modelling p_{md} would approach 50% and p_{fa} 25%.

For an SBAS system, both probability density terms are under the control of the SBAS system. The probability of false alarm in SBAS could for example be improved through improved position/clock corrections (reducing URE) or greater error bounds (increasing Thr). For an integrity monitoring system, these options do not exist. The DIM System cannot establish suitable monitoring pre-conditions (in terms of model noise and mean, with respect to σ_{URA}) without knowledge of performance of the underlying GNSS. This performance will of course not be uniform for all monitored satellites. Older GPS satellites may have worse URE statistics than the most recent launches [Heng 2011]. Statistics may also evolve with GNSS central system prediction capabilities, and not be constant over time even for the same satellite.

3.2.5.2 The Significance of Requirement [C0160]

Requirement [C0160] specifies a false alarm rate of 1e-5 per epoch. The requirement must be seen within the context of the additional assumptions and clarifications included in [INS Req]. [INS Req] elaborates that the mandated false alarm rates are driven by maritime continuity requirements. [INS Req] Assumption 5 clarifies that the mandated false alarm rate applies to "RAIM false-alarms (1e-5 per independent epoch)" where Assumption 1 defines an independent epoch to be 150s. A user RAIM false alarm directly results in the loss of the user position. By contrast, a false DIM Service alarm on a single satellite does not inevitably lead to a user RAIM false alarm. Rather, the impact of a false alarm depends on the availability of sufficient other satellites to continue with a position solution, excluding the falsely flagged satellite. Therefore, DIM Service false alarms contribute to the RAIM false alarm rate at a much lower rate. Furthermore, the budget for DIM Service false alarms depends on the overall availability and redundancy provided by the constellation. A DIM Service false alarm rate of any false alarm across all satellites of a constellation between 1e-3 and 1e-4 per independent 150s epoch is expected to be realistic and sufficient to constrain the DIM Service contribution to the RAIM target.

We note in this context [EGNOS SDD]: "*The minimum continuity risk performance is less than 10^{-4} per 15 seconds in core part of ECAC landmasses, and less than $5x10^{-4}$ per 15 seconds in most of ECAC landmasses. There are however some regions with a risk of over 10^{-3} per 15 seconds. Such a minimum performance is not compliant to ICAO requirements for Category I precision approach as described in Table 6-1 ($8x10^{-6}$ per 15 seconds).*"

3.2.5.3 Feared Events

Requirement [A0040] obliges the DIM Service to notify the user of the presence of feared events (onboard clock jumps or ramps, cycle slips or corrupted signals as elaborated in section 3.3.1.1 below) even if the resulting ranging error remains bounded by the relevant

URA or SISA. For these situations, decision and alarm thresholds must be defined, in terms of magnitude of cycle slip or clock jump, or the strength of the evil wave form signal. These thresholds represent the minimum detectable size of feared event and must be consistent with overall DIM Service p_{fa} and p_{md} targets. An event such as an on-board clock jump of magnitude below its decision threshold is not considered significant to the user and will not be considered a missed detection for the purposes of performance evaluation against requirement [A0040]. Section 6.4 below reports the initial assessment performed as part of the current study.

3.2.6 Approach to Multiple Faults

Both GPS [SPS 2020] and Galileo [OS SDD 2021] place the probability of misleading information (i.e., the broadcast accuracy does not overbound the actual user range error) below 10^{-4} per hour per satellite globally. Whilst this might indicate that incidents of multiple satellite failures will have negligible probability of occurrence from a user perspective such incidents have of course been observed, potentially suggesting that incidents on different satellites are not entirely uncorrelated. For this reason, and considering that the number of satellites will increase, this study must consider the impact of multiple failures in scope.

Where algorithms process lines of sight or satellites individually, fault detection and isolation capabilities are robust by design to simultaneous faults on multiple satellites. However, any models where measurements from multiple satellites are combined require dedicated fault isolation steps. If a satellite is identified as faulty only after it has contributed to joint models the cycle's processing must be repeated without the faulty satellite. The fault detection and isolation strategy therefore requires the systematic retention of the previous model state.

It is expected that, in the case of multiple failures the DIM information and systematic exclusion of faulty satellites will be of particular benefit to RAIM performance.

3.3 Threats and Feared Events

DIM System modelling must address and mitigate two groups of threats or feared events. In addition to the applicable subset of user level threats and feared events identified in [INS Thr], additional threats and feared events are inherent in the design of the integrity monitoring system itself.

3.3.1 User Level Threats

[INS Thr] identifies seven categories of faults and threats at user level. Categories 4 (ionospheric disruption), 5 (local faults such as multipath), and 6 (spoofing and jamming) are specific to the user's environment and line of sight and cannot be monitored centrally. Category 7 relates to faults of SBAS services, which is not applicable to the present study.

3.3.1.1 Single Satellite Faults

[INS Thr] Category 1 faults relate to individual satellite faults and are the primary object of DIM System monitoring. Whilst there are numerous causes of fault, from an integrity perspective only their impact on the measurement must be monitored. An attribution to a specific cause is not required.

[INS Thr] therefore groups the Category 1 faults into satellite clock jumps and ramps, corrupted signal (such as evil waveform), and bad ephemeris.

3.3.1.2 Faults of Multiple Satellites

[INS Thr] Category 2 concerns the simultaneous occurrence of Category 1 faults for multiple satellites. As discussed in Section 3.2.6 above, the DIM System level modelling offers significant opportunities for fault detection and isolation, especially in the event of two faults. Higher numbers of simultaneous faults will gradually erode the detection capabilities of any system. Their probability of occurrence is expected to be sufficiently low to justify their exclusion from the modelling.

3.3.1.3 Whole or Inter-Constellation Faults

[INS Thr] Category 3 concerns faults affecting a whole constellation or the parameters governing the relationship between the two constellations. The approach to GGTO and the relationship between two constellations is discussed in Section 3.2.1 above.

3.3.2 Threats at Integrity Measurement Stations

The threats and faults applicable to Integrity Measurement Stations (IMS), and mitigations available, naturally depend on the overall system architecture of the DIM System. Most threats and faults relating to measurement stations present similar signatures as the threats and faults originating in GNSS. The separation of origin for any such signals is critical to the integrity monitoring system. If IMS faults are incorrectly attributed to GNSS, availability, continuity and false alarm performance will be impaired. If GNSS faults are incorrectly attributed to IMS, integrity will be impaired. The following subsections present the IMS faults and threats to be accounted for.

3.3.2.1 IMS Clock Jump and Instability

IMS clocks are expected to be free running but steered, with stable drift with respect to GPS and Galileo network times. Assuming IMS clocks are modelled at all (see Section 3.4.5 below) the attribution of jumps or instability within a measurement series to an IMS clock will require statistically significant numbers of lines of sight of the particular affected IMS, without simultaneous equivalent incidents at other IMS.

3.3.2.2 IMS Inter-System Bias Instability

[Paziewski 2015] reports that whilst hardware ISB can take significant values, for professional receivers short- and medium-term stability of the ISB and consistency across the different channels of the same receiver can be expected.

As discussed in Section 3.2.1 on GGTO, hardware ISB is inextricably linked to the receiver clock, so that in a multi-constellation GPS-Galileo environment effectively two receiver clocks will be modelled. ISB instability will then manifest itself in the same way as actual IMS clock instability and will be attributed according to the same statistical evaluation.

3.3.2.3 IMS Multipath

The selection of suitable locations to house IMS requires extensive site surveys and cannot be part of the present study. One of the key criteria of site surveying is the absence of multipath. The present study therefore makes the assumption that sufficient suitable sites can be identified with adequate geographic spread which exhibit low multipath.

Nevertheless, the DIM System modelling must guard against multipath. Multipath detector filters are well established, and if sites are suitably selected, the rare exclusion of genuinely multipath affected lines of sight is deemed affordable from a performance perspective. Care will need to be taken to protect the multipath filter from false positives which may arise from unrelated conditions such as IMS or GNSS clock jumps and cycle slips.

3.3.2.4 IMS Cycle Slip

The presence of one or more cycle slips within an individual single frequency measurement series may reflect a variety of underlying causes other than genuine receiver cycle slips, namely environment (ionospheric scintillation), IMS clock jumps, GNSS clock jumps, and GNSS signal issues. The DIM System modelling must therefore perform the statistical evaluation of the full set of concurrent measurements in order to attribute any detected cycle slips to their correct causes.

3.3.2.5 Scintillation and Other Ionospheric Disturbances

Elementary spherical geometry calculations demonstrate that ionospheric pierce points will be within a 20-degree spherical angle of the IMS location for measurements above 10 degrees elevation. [Nguyen 2022]'s map of current ionospheric disturbances shows that some observations from UK IMS of GNSS satellites rising in the West will pass through Southern Icelandic regions with a raised, but not highest, level of ionospheric disturbances.

Scintillation and other ionospheric phenomena will be reflected in greater phase noise and impaired signal to noise ratio, ultimately up to the loss of the tracking loop lock. The exact representation in measurement data will depend on receiver hardware and receiver configuration.

[Nguyen 2022]'s map furthermore highlights that a mariner within the UK EEZ to the North or West of the UK must expect to experience a significantly higher level of scintillation compared to what is observable from onshore UK. The movement of the magnetic North pole (50km East per year) may cause a further deterioration of ionospheric conditions in regions visible from the UK EEZ. We conclude that an alert mechanism regarding ionospheric disturbances would clearly be of interest in the Northern and Western parts of the UK EEZ but cannot be provided by a System based exclusively onshore in the UK.

Whilst scintillation and other atmospheric disturbances represent a major, if not predominant, cause of tracking loop loss of lock for GNSS receivers, loss of lock may of course also be caused by other GNSS signal disruptions. In this case, the GNSS satellite would be classified automatically as 'not monitored' due to lack of observations, and no integrity asserted. The DIM System will not be designed to derive satellite alarms from tracking loop losses of lock, due to the expected predominance of false positives.

3.3.2.6 IMS Jamming and Spoofing

The impact of any jamming or spoofing attack on an integrity monitoring system depends on the nature of the attack. For a local attack on a single IMS, the redundancy of IMS locations will mitigate the loss of measurements, or the presence of bad measurements from a single IMS. A co-ordinated attack on a majority of IMS would be unprecedented, but equally unmitigable. Security measures against a denial-of-service attack are outside the scope of the present study. We may add that the generation of misleading information (i.e. a satellite being spoofed to appear OK to the system whilst it is in fact faulty), would require a very sophisticated attack, including the anticipation (or triggering) of the in-orbit fault.

Operationally, it may be of interest to establish an independent interference detection capability around IMS sites, especially to detect any systematic patterns or prolonged interference events, which may inform longer term off-line performance monitoring of the DIM System and additional security measures. The selection of appropriate interference detection capability is outside the scope of the present study.

3.3.2.7 Data Gaps

Data gaps occur within series of measurements, affecting one or more frequencies of the line of sight. The overwhelming majority of data gaps in an integrity monitoring system trace to IMS, environment, and network issues. Therefore, the system will not use data gaps as indicators of satellite faults. Nevertheless, data gaps require special attention in order to prevent the contamination of the detectors and filters.

3.3.2.8 IMS Misattribution and False Lock

The false locking of a receiver to a GNSS signal, on one or more frequencies, represents a well-known threat to the integrity of system level integrity monitoring. Instances include the complete misattribution of a PRN code as another PRN, or code errors in the order of 10-100 meters in one frequency. The system must establish barriers which detect and eliminate affected measurements. Misattributions can be detected through consistency checking against the GNSS almanac, other false locks through consistency and plausibility checks of the measurement series, as well as the exclusion of measurements falling below a minimum signal to noise threshold.

3.4 Processing Model

The algorithmic processing and fault detection model of the DIM System will be distributed between the IMS and a central processing unit. The present section defines the selected algorithms and sequence of processing.

3.4.1 Integrity Monitoring Stations

All modelling is based on the quality of available measurements. For this reason, the location and capability of the receivers is key to the overall DIM System performance. The requirements on receivers include:

- Locations shall be surveyed and selected to minimise local multipath.
- Receivers shall be of professional performance level.
- Receivers shall be selected for hardware short- to medium-term ISB stability.

- Receiver inter-channel biases (when measuring the same satellite) shall have been fully calibrated.
- Receivers shall support the monitoring of evil wave forms.
- Receivers shall autonomously monitor measurement quality, including tracking loop status and suspected multipath, jamming.
- IMS and data network reliability shall be commensurate with safety criticality.

3.4.2 Measurement Validation and Filtering

All measurements will be validated and filtered on an individual line of sight basis, in order to prevent the contamination of other measurements or satellite models.

3.4.2.1 Satellite Position

Satellite Positions shall be computed as per [GPS ICD] and [Galileo ICD] including relativistic corrections.

3.4.2.2 Measurement Exclusion

Measurements will be excluded from further processing if the IMS quality information indicates tracking issues, multipath or jamming. Measurements will furthermore be required to surpass a minimum, elevation dependent, signal to noise ratio as a means to exclude poor quality measurements.

The above exclusion criteria address symptoms local to the IMS and not underlying satellite faults. Offline analysis may monitor the rate of incidents in order to determine any systematic issues with the IMS hardware or location.

3.4.2.3 Measurement Series Outliers

The algorithm shall use polynomial extrapolation of the measurement series of code, phase, code minus carrier, and consistency across all frequencies potentially used for dual frequency ionosphere-free combinations in order to detect outliers among the latest measurements.

Measurements identified as outliers shall not be passed into final satellite modelling but will still be passed through the cycle slip detectors in order to support the statistical evaluation and attribution to either IMS or satellite issues.

The outlier thresholds employed represent the minimum detectable signature of feared events onboard a GNSS satellite. The thresholds shall be chosen to be consistent with the IMS's measurement noise of the respective measurement elements.

3.4.2.4 Troposphere Correction

Following [Martelluci 2009], the performance of the Saastamoinen model is considered adequate for the targeted level of modelling noise.

3.4.2.5 Cycle Slip

The need both to protect subsequent modelling from any cycle slips and to distinguish multiple causes of perceived cycle slips leads us to propose two cycle slip detection mechanisms.

For protection, a third order difference model, with limited polynomial extrapolation in case of single cycle data gaps, will eliminate any phase instabilities.

For disambiguation, the dual frequency geometry free combination model as per [NAV CS] is preferred due to its ability to eliminate contributions from both IMS and GNSS clock jumps.

The algorithm shall attempt to repair only genuine cycle slips. Ionospheric disturbances, such as scintillation, are expected to result in multiple consecutive cycle slip detections and require full re-initialisation of the line of sight.

3.4.2.6 Multipath

The standard test which tracks extrema in the code minus carrier observable (see for example [NAV MP]) is considered adequate because major multipath events are expected to be rare if IMS site environments have been correctly surveyed. In line with the expected rarity of multipath events, no repair will be required or attempted. For the successful operation of the multipath algorithm, it must at all times be protected from inputs containing cycle slips or clock jumps.

We note that multipath detection through filtering is not instantaneous but delayed to the detection of extrema. Mitigation lies both the site selection and in the exclusion of measurements from satellite modelling until continuous measurements have been received for a period sufficient to evaluate multipath.

3.4.2.7 Ionosphere and Smoothing

The fully corrected measured range shall be computed as the ionosphere-free carrier smoothed code through the algorithm of [NAV SMOOTH]. This algorithm passes the ionosphere-free combination of pseudoranges through a dual frequency hatch filter, using dual frequency phase measurements. The algorithm is consistent with the ionosphere-free combinations prescribed for dual frequency users by [GPS ICD] and [Galileo ICD] as well as [DFMC SARPS].

3.4.2.8 Other Corrections

Corrections for tides (ocean and solid earth) and Sagnac effect are not considered necessary for DIM System modelling because the magnitude of these effects is expected to be below the level of noise inherent in measurements. The receiver phase centre does not require a dedicated correction because it will be absorbed into the receiver clock models.

3.4.3 GNSS Ephemeris Broadcast Validation

The DIM System shall monitor the broadcast ephemerides. The focus of monitoring will be on inconsistencies which require continuous observation and may not be detectable by an instantaneous RAIM. Checks shall include:

- Verification of position consistency between consecutive navigation data sets at the point of ephemeris updates to ensure smooth user transition;
- Compliance with rules covering IOD repetition (IODE in case of GPS) for the protection from mismatches;
- Status of satellite's own broadcast health indicators;
- [GPS ICD] / [Galileo ICD] compliance.

3.4.4 Exploitation of Exclusion Statistics

In order to attribute any observed measurement outliers and cycle slips correctly to either the DIM hardware itself, or the monitored satellite, the DIM System will exploit the statistics of excluded measurements for each epoch.

If a statistically significant majority of all measurements of a single IMS exhibits statistically significant outliers, then the DIM System algorithm shall detect an IMS fault event and eliminate all measurements of the affected IMS from subsequent modelling.

Conversely, if a statistically significant majority of all measurements of a single GNSS satellite exhibits statistically significant outliers, or are flagged for evil wave form, then the DIM System algorithm shall detect a satellite fault and eliminate all measurements of the affected satellite from modelling. The alarm thresholds, along with the detection thresholds of sections 3.4.2.3 and 3.4.2.5, shall be chosen such that the resulting false alarm rate remains below its allocation.

Some effects such scintillation neither reflect on IMS nor satellite but may nevertheless impair more than a single line of sight. The DIM System algorithm will therefore attempt to maximise the statistical basis of the exploitation, and in particular expose measurements to the cycle slip tests even if they were already flagged by earlier outlier detection.

3.4.5 Modelling of IMS and Satellites

Having accounted for, through correction or mitigation, all other non-negligible measurement biases in the pre-processing and validation, the measurement equation for the residual range $\Delta\rho$, which is the difference between geometric distance and measured range, becomes:

$$\Delta\rho = \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} \cdot \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \end{pmatrix} + c(\Delta t_{rx} - \Delta t_s) + \varepsilon$$

Where $(u_x \quad u_y \quad u_z)$ is the unit vector from receiver to satellite, $(\Delta x \quad \Delta y \quad \Delta z)$ is the satellite position error, which is the difference between actual position and ephemeris broadcast, Δt_s is the satellite clock error, and Δt_{rx} the receiver clock error, both with respect to the network time of the satellite's constellation. ε represents the residual measurement noise including any residual higher order effects of corrected biases as well as biases which were not corrected due to their low magnitude.

With four parameters per satellite, and one per constellation per receiver, an elementary calculation demonstrates that for 5 or more receivers, the number of measurements exceeds the number of modelled parameters, assuming N visible satellites per constellation, of which at least N-2 are tracked by each receiver. However, as already conceptually explored in Section 3.2.2, the unit vectors $(u_{xr} \quad u_{yr} \quad u_{zr})$ from all receivers r to a given satellite will be almost parallel, resulting in near singular inversion matrix of the least squares problem.

The objective of the modelling is to estimate the residual range error at the worst user location in the UK EEZ. It may therefore not be necessary to model all individual components of the satellite error. The satellite error components Δx, Δy, Δz, Δt_s combine into the residual range error at the receiver location. The collection of samples from all receivers can be used to estimate the error within the geographic polygon defined by the receiver locations. Additional extrapolation and or adapted integrity assurance levels may be sufficient to cover the worst user location within the UK EEZ.

The receiver clock error constitutes an auxiliary parameter. A priori, the receiver clock component, along with ISB, might be eliminated through single differencing of the residual ranges. This would however combine all satellites of a constellation into a joint model, resulting in greater numerical complexity of resolving the much larger number of model parameters within a single estimation, greater risk of contamination by a single faulty satellite, and reduced fault isolation capability.

The study therefore concludes to model receiver clocks and the pseudorange errors.

3.4.5.1 IMS Clock Modelling

With a free-running receiver clock the contribution of the receiver clock to the residual range error will dominate by orders of magnitude and be detrimental to the numerical accuracy achievable for the other modelled parameters. We use the underlying stability of the receiver clock to extrapolate the bias and deduct the extrapolated bias from the residual error.

As per Section 3.2.1 above, IMS clocks must be modelled per constellation. The basic input into the IMS clock model is the average of the pseudorange error residuals of the satellites of the given constellation. Due to the expected stability of the IMS clocks, a second order polynomial interpolation over a suitably selected sliding window is expected to be appropriate for modelling purposes.

3.4.5.2 Fault Detection and Isolation

In order to protect the stability of the IMS clock model, the preselection of residuals is essential. By construction of the algorithm, only fully smoothed pseudoranges will be available which were not previously flagged as faulty.

The clock model utilises the observations of multiple satellites and is therefore exposed to any satellite fault or local measurement error. The exclusion of a line of sight which previously contributed to the average, be it due to subsequent fault detection or setting satellite, has the potential of creating model instability. Insufficient sample size, such as fewer than 4 residuals contributing will lead to unreliable outlier detection.

The algorithm shall address these considerations through the iterative exclusion of any satellite subsequently identified as faulty or not monitored and shall repeat the IMS clock modelling based on the final set of continually monitored satellites only. Where insufficient measurements remain for an epoch, the epoch shall be excluded from interpolation.

3.4.5.3 Satellite Pseudorange Error Modelling – Integrity Test

In line with the conclusions of Section 3.2.2, the preferred algorithm will not attempt to model an error surface or trend, but will consider the sample set of residuals as a normally distributed set of samples around the actual residual error at the centre of the polygon enclosed by the IMS locations.

For a given epoch, let $Mean_{Model}$ represent the mean of the sample set of n pseudorange residuals, with sample variance σ_{Model}. Let σ_{URA} be the 1-σ broadcast bound and $k_{maritime}$= 4.42 be the scaling factor corresponding to maritime use.

Figure 3-3 illustrates the distribution of the true satellite residual error for this model.

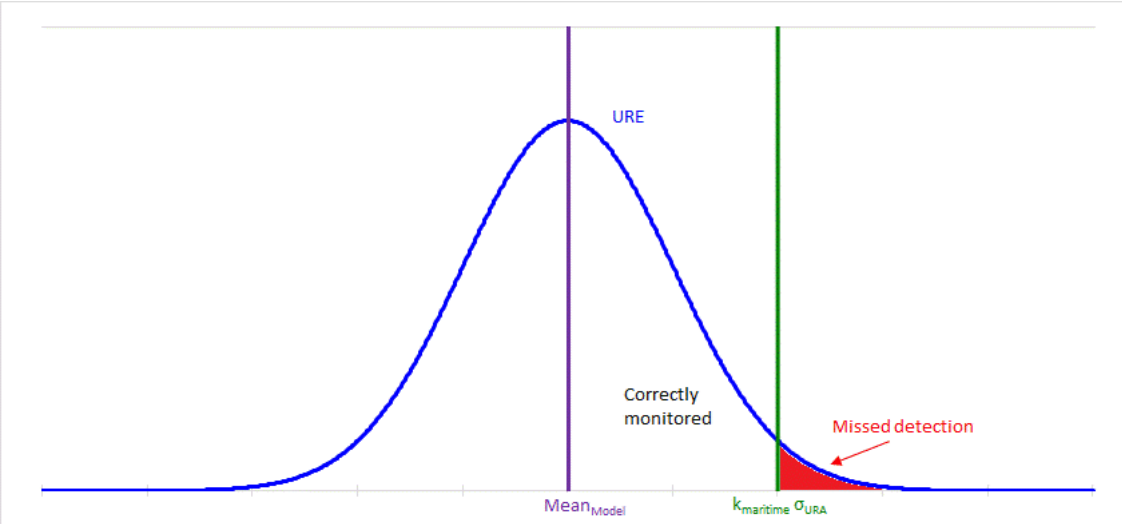


Figure 3-3 True Residual Error Distribution

Given a modelled mean of n residual measurements and provided the measurement errors underlying the individual residuals are normally distributed, the true residual error URE will be distributed as a Student distribution of $n-1$ degrees of freedom around the mean, scaled by the sample variance. The distribution's right tail represents the missed detection probability.

It is well known (and will be confirmed again by the PoC Experimentation section 6.2 below) that the tail of GNSS measurement error distributions does not follow a strict normal distribution but exhibits a larger tail. Furthermore, as per Section 3.2.2 above, the algorithm will absorb any potential trend in projected error into the sample variance rather than mean.

An exact modelling of the true satellite error at worst user location, SREW, becomes therefore prohibitively complex. An approximation of the distribution by a Student distribution of $n-1$ degrees of freedom has however been used successfully in SBAS. Therefore, the alarm condition for users within the polygon of IMS locations is represented by the test:

$$\frac{k_{maritime} \cdot \sigma_{URA} - Mean_{Model}}{\frac{\sigma_{Model}}{\sqrt{n-1}}} > t_{1-\frac{p_{md}}{2}}$$

Where $t_{1-\frac{p_{md}}{2}}$ bounds the fractal of the Student distribution corresponding to the acceptable missed detection probability. The satellite is considered in alarm if the condition evaluates as FALSE. The minimum number of observations required to successfully monitor a satellite will be experimented in the PoC Testbed, see section 6.5.2 below.

3.4.5.4 Alternative Satellite Error Modelling – Geometry Inversion

Alternatively, the ensemble of pseudorange residual errors of a given satellite may be used to estimate the complete 4-dimensional error of the satellite employing an observation matrix H

$$\begin{pmatrix}\rho_1\\ \rho_2\\ \dots\\ \rho_n\end{pmatrix} = H\begin{pmatrix}\Delta_x\\ \Delta_y\\ \Delta_z\\ \Delta_t\end{pmatrix} = \begin{pmatrix}u_{1x} & u_{1y} & u_{1z} & 1\\ u_{2x} & u_{2y} & u_{2z} & 1\\ \dots & \dots & \dots & \dots\\ u_{nx} & u_{ny} & u_{nz} & 1\end{pmatrix}\begin{pmatrix}\Delta_x\\ \Delta_y\\ \Delta_z\\ \Delta_t\end{pmatrix}$$

Where $(u_{rx} \quad u_{ry} \quad u_{rz})$ are the unit vectors from receivers $r, r \in \{1, \dots, n\}$ to the modelled satellite, $(\Delta x \quad \Delta y \quad \Delta z)$ is the satellite position error, which is the difference between actual position and ephemeris broadcast, and Δt is the satellite clock error, with respect to the average clock observed by the user. An estimate of the true satellite error can therefore be obtained from

$$\begin{pmatrix}\Delta_x\\ \Delta_y\\ \Delta_z\\ \Delta_t\end{pmatrix} = (H^T H)^{-1} H^T \begin{pmatrix}\rho_1\\ \rho_2\\ \dots\\ \rho_n\end{pmatrix}$$

provided there are sufficient observations with sufficiently diverse geometry unit vectors. For suboptimal geometries, variants of the algorithm exist which constrain the satellite error estimate in the poorly observable directions, effectively creating a hybrid between a mean model and a full 4-dimensional inversion.

The algorithm then projects the estimated 4-dimensional satellite error to all locations within the UK EEZ, thus identifying the user location which experiences the worst, that is, biggest absolute pseudorange error. The satellite residual error at the worst user location is then compared against the scaled broadcast URA or SISA, as per definition of the decision threshold for satellite alarm.

The PoC Experimentation of sections 6.2 and 6.5.3 below will explore both the alternatives of sections 3.4.5.3 and 3.4.5.4.

3.4.5.5 Alternative Satellite Error Modelling – WAAS Approach

[Walter 2018] provides a valuable insight into the WAAS approach to satellite error modelling. The WAAS model effectively builds the satellites' UDRE error bounds bottom up from the noise encountered by the observables extracted from the ensemble of measurements which contribute to the satellite position model. Thus, the WAAS algorithms do not perform an ultimate test of integrity against a decision threshold. WAAS satellite alarms will only be used to communicate significant issues to the users which can no longer be addressed by increasing the UDRE error bound.

By contrast, other SBAS systems establish a UDRE value, and subject it to a top-level, independent integrity test. This integrity test compares a modelled upper bound of the satellite error against a decision threshold related to the proposed UDRE.

The DIM Service is designed to test integrity, but not to augment the GPS URA or Galileo SISA by means of a UDRE. Therefore, the DIM Service's needs are conceptually closer to SBAS systems with top-level, independent integrity test. This is reflected in the algorithmic philosophy proposed by the current study.

3.4.5.6 False Alarm

Figure 3-4 illustrates the bi-variate distribution underlying the DIM System's false alarm modelling. It maps the probability density of the false alarm calculation in section 3.2.5.1 above. The horizontal axis represents the Student distribution of the mean of n samples around a true residual error URE, and the resulting Res_{Model} test statistics underlying the alarm condition in section 3.4.5.3. The vertical axis represents the χ^2 distribution (of one

degree of freedom) of the term $URE - k_{maritime}\,\sigma_{URA}$. The probability density function is colour coded by value, except for the yellow zone, which represents the area of false alarms.

A false alarm from final satellite modelling occurs if and only if

$$Res_{Model} > k_{maritime}\,\sigma_{URA} \quad \&\& \quad URE - k_{maritime}\,\sigma_{URA} < 0$$

Where

$$Res_{Model} = Mean_{Model} + t_{1-\frac{p_{md}}{2}} \frac{\sigma_{Model}}{\sqrt{n-1}}$$

The exact distribution, and in particular the degree of separation between the peak of the density and the yellow zone depend on the underlying GNSS performance. **Figure 3-4** illustrates the case where $URE = \frac{1}{2}\,\sigma_{URA}$ and the IMS measurement sample variance equals URE, for 5 validated samples. As per [Heng 2011] these parameters represent a conservative case for GPS. Sampling standard deviation is set to 0.4m. These numerical assumptions are subject to experimentation in section 6 below.

Different GNSS performances, in terms of ratio between URE and σ_{URA}, and different IMS performances, in terms of number and variance of samples would need to be aggregated in order to confirm the DIM System modelling cumulative false alarm performance.

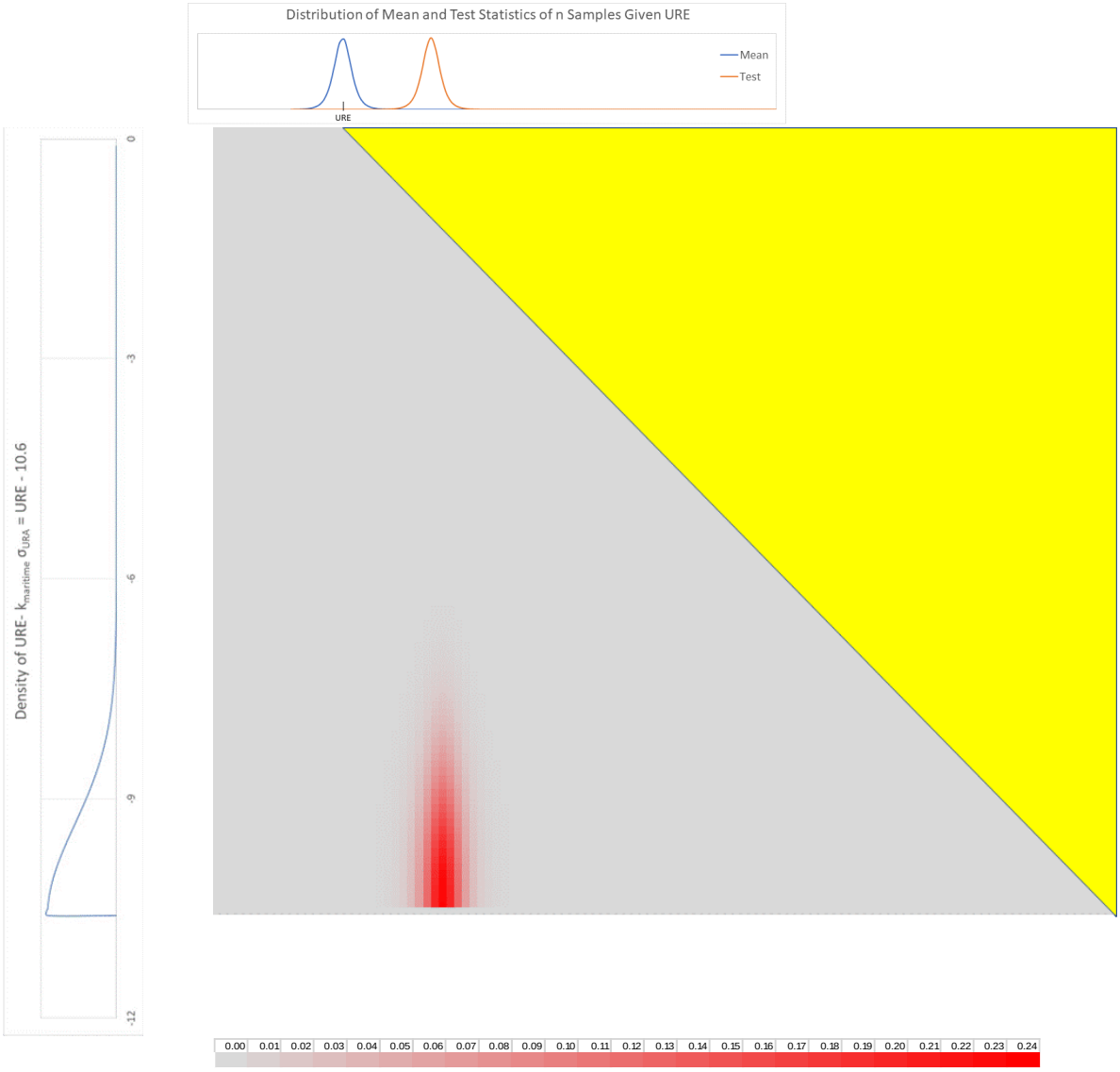


Figure 3-4 False Alarm

As previously identified, for certain combinations of true error, sample mean and sample variance, the probability of false alarm will significantly exceed the target false alarm rate p_{fa} derived from requirement [C0160]. However, in aggregate it is expected that the cumulative distribution within the yellow zone is within budget because the broadcast σ_{URA} significantly exceeds the true URE.

In the event of the resulting false alarm probability of the proposed DIM System algorithm exceeding its allocation, the algorithm may be adapted to exclude samples with large sample variance (relative to $Mean_{Model}$ and σ_{URA}) by setting the affected satellite 'not monitored' instead. We highlight however that a 'not monitored' status for a satellite which breaches the alarm threshold still represents a missed detection in the sense of requirements [B0070] and [B0090]. Therefore, should such a 'monitorability' pre-condition be required, the missed detection model will also need to be revisited.

3.4.5.7 Extrapolation to UK EEZ

Section 3.4.5.3 developed an alarm condition for the polygon enclosed by the IMS locations. As per section 3.2.2 above the DIM Service for the full UK EEZ must account for the possibility that lines of sight for mariners create worse user error than is observable onshore.

The total error vector covered by σ_{URA} decomposes into two independent error components, the one observable from the UK onshore, and the one not observable because of orthogonality to the IMS lines of sight. Even at worst user location, the mariner will only be able to observe less than 4% of this orthogonal error component. Conversely, both the mariner and UK onshore assets will observe radial and satellite clock errors (which statistically dominate) almost in their entirety.

In the absence of sea-based measurements two alternative approaches may be considered. The first approach involves an acknowledgement that the sea-based missed detection probability will be inferior to the assurance for shore-based or port users. The second approach accounts for the orthogonal error component by inflating both its $Mean_{Model}$ and its variance σ_{Model} by a factor k_{GDOP}. The PoC experimentation of section 6.2.3 below presents initial performance estimates for both approaches. The final selection will need to be documented in the DIM Service Standard to allow the DIM Service user to derive correct protection limits.

3.5 Performance Expectation

Several aspects of the DIM Service performance are subject to experimentation as per section 6 below. As seen before, the achievable performance of the DIM System depends both on the performance of the GNSS being monitored, and the representative quality of the input measurements. Performance simulation assumes that the quality and distribution of measurements must be as mandated.

3.5.1 Service Volume - Availability

The DIM Service will maintain a ‘not monitored’ amber status for rising or setting satellites which may be visible to some users. A user 400km to the West of the UK shore (approximately 5 degrees longitude at UK latitude), will have visibility of a satellite rising in the West around 10 minutes ahead of onshore UK. Convergence of the DIM System models will require another 10 minutes before the DIM System is able to confer ‘monitored’ green status. In total, the user may be prevented from using the rising satellite’s measurements for approximately 10% of a typical satellite pass. The impact is mitigated by the consideration that these 10% are low elevation observations with associated low weight within any MRAIM solution.

3.5.2 User Position Accuracy

User positioning accuracy continues to depend primarily on GNSS accuracy and on user specific local circumstances and environmental conditions.

In the fault free case, the DIM Service assures integrity but does not improve accuracy beyond the underlying accuracy of the user solution based on the GNSS broadcast. On average, the DIM Service will marginally reduce accuracy as a result of false alarms on satellites which would otherwise have contributed positively to the user’s positioning.

In the faulted case, the successful detection of satellite issues will improve user accuracy in cases where the MRAIM algorithm is unable to determine cause or eliminate the source.

3.5.3 False Alarm and Missed Detection Probability

False Alarm and Missed Detection probabilities a priori arise in every algorithm step of the processing model in section 3.4 above. Their sum totals represent the associated probabilities of the DIM Service.

For the contribution from IMS (section 3.4.1), requirements will need to be placed on the selection of hardware constraining the p_{fa} and p_{md} of IMS quality flags, including evil wave form, output.

The algorithms of section 3.4.2 exclude measurements from further processing. Detected threshold breaches do not directly lead to satellite alarm. However, the tests of sections 3.4.2.3 and 3.4.2.5 contribute to the statistical evaluations of section 3.4.4 via the selected threshold values.

The algorithms of section 3.4.3 implement logical tests with no associated p_{fa} or p_{md}, as long as the risk of measurement misattributions (to a different PRN) is negligible.

The statistical evaluations of section 3.4.4 directly contribute to the overall false alarm rate p_{fa}. We recall that, by construction, small magnitude feared events below their respective decision thresholds will not be considered feared events, and therefore do not contribute to missed detection statistics p_{md}.

Evaluation of the distributions shown in **Figure 3-4** yields a false alarm rate of p_{fa} < 2e-6 per modelled satellite per 1s. Considering the high correlation between consecutive measurements of the same line of sight, this scales to below 2e-5 per 150s per satellite and 1e-4 per 150s across all satellites of a constellation. We note, however, that the distributions underlying this computation are approximations with multiple known simplifications.

3.5.4 Time to Alarm

The time to alarm is composed of four elements. The IMS require 1 second to take measurements. This is followed by one second to transfer the measurements to the DIM System processing facility. Processing itself will require a fraction of a second.

The main driver of time to alarm is therefore the dissemination of the DIM Service messages to the user. For a target TTA of 10 seconds, dissemination must be facilitated within 7.5 seconds.

3.5.5 Conclusion – Summary of DIM Service Contributions

For a user operating an MRAIM algorithm, the DIM Service provides a range of supplementary Integrity assurance information which would not be available to the user's single receiver:

- Statistics of observations from multiple receivers will allow to attribute faults such as cycle slips unambiguously to either satellite or receiver.
- High specification receivers will be able to monitor for conditions such as evil wave forms not available to user receivers.
- Continuous monitoring facilitates consistency checks against historic information which a newly initialised user receiver may not have.
- In the event of multiple faults, the ability of the central system to isolate multiple faults is greater due to the number of available measurements.

4 ARCHITECTURE AND DESIGN

This section presents the architecture and functional design of an integrity monitoring system for dual frequency multi-constellation (DFMC) GNSS over the UK European Exclusive Economic Zone (UK EEZ) based on UK based monitoring assets only. The architecture and design were created under WP7.2 and WP 7.3 of the INSPIRe Programme.

The section develops a high-level conceptual and physical system architecture, required to be developed and deployed for the DIM Service, including data flows, as well as a functional design of its key system components. Synergies with other UK based GNSS monitoring systems are explored in support of development and operational efficiencies.

Section 4.1 presents the conceptual architecture of the DIM System.

Section 4.2 develops the physical architecture including geographic distribution and redundancy.

Section 4.3 explores potential synergies with the GENS UK based GNSS monitoring system.

Section 4.4 develops the functional design of key architecture elements.

4.1 DIM Conceptual Architecture

Figure 4-1 presents a DIM System conceptual architecture. Whilst the focus is on the maritime sector in principle the architecture could equally support a UK-wide DFMC integrity monitoring for other application domains.

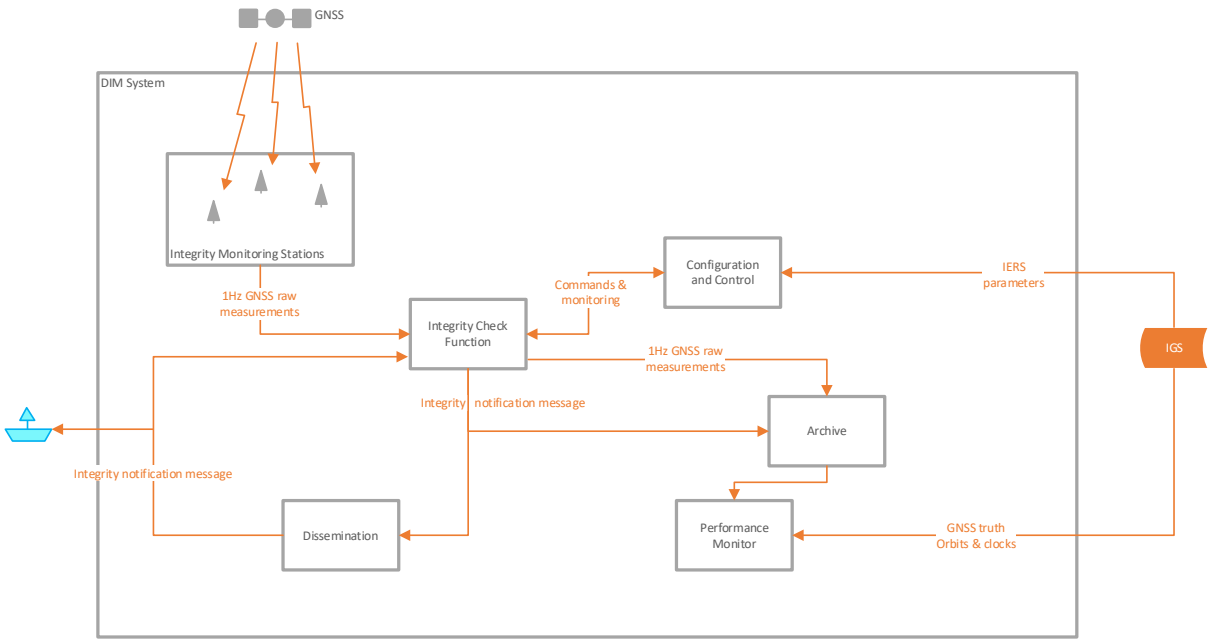


Figure 4-1 DIM Conceptual Architecture

4.1.1 Integrity Monitoring Station

Integrity Monitoring Stations take range and phase measurements of GPS L1, L5 and Galileo E1, E5a, E5b signals at 1Hz frequency, and communicate these to the Integrity Check Function. Integrity Monitoring Stations supplement raw measurements with quality indicators relating to their signal tracking and processing, including jamming, signal-to-noise ratio, cycle slip, multipath and evil waveform indicators.

4.1.2 Configuration and Control

Configuration and Control is responsible for the deployment, configuration, and operation of the DIM System elements. Configuration and Control solicits monitoring messages of the system state from each DIM System element.

4.1.3 Integrity Check Function

The Integrity Check Function assesses the integrity of the monitored GNSS satellites based on the measurements taken by the Integrity Monitoring Stations and provides one Integrity Notification Message per second to the Dissemination Function for distribution to the users of the DIM Service.

The Integrity Notification Message communicates a green (monitored), amber (not monitored), red (alarm) status for each satellite. The significance of the satellite statuses is defined in the algorithm specification section 3.1. A copy of the Integrity Notification Message is returned to the Integrity Check Function to confirm correct distribution. In case of detected corruption, the Integrity Check Function will be able to stop the DIM Service.

4.1.4 Dissemination Function

The Dissemination function facilitates the dissemination of one Integrity Notification Message per second to the users. It is proposed that this integrity service shall be implemented as an e-Navigation Service on the Maritime Connectivity Platform (MCP).

The MCP is a conceptual, carrier agnostic, data communications and dissemination platform for sending electronic data between ships and shore-based infrastructure. This data is intended to underpin a number of automated e-Navigation services, with individual users electing to subscribe to receive data based on their navigation needs or geographical location.

The MCP itself consists of three components:

1. Maritime Identity Registry (MIR) serves the security of the MCP by containing a registry of unique identities for all maritime vessels and users and also acts as the certificate authority for the public-private-key cryptography, which underpins all communications over the MCP.
2. Maritime Service Registry (MSR), performs the same task of maintaining an identity registry for service providers, and enables the maritime user to look up and subscribe to various e-Navigation services.
3. Maritime Messaging Service (MMS) provides the architectural interface between shore-based service providers, and the hardware and crew on the vessel.

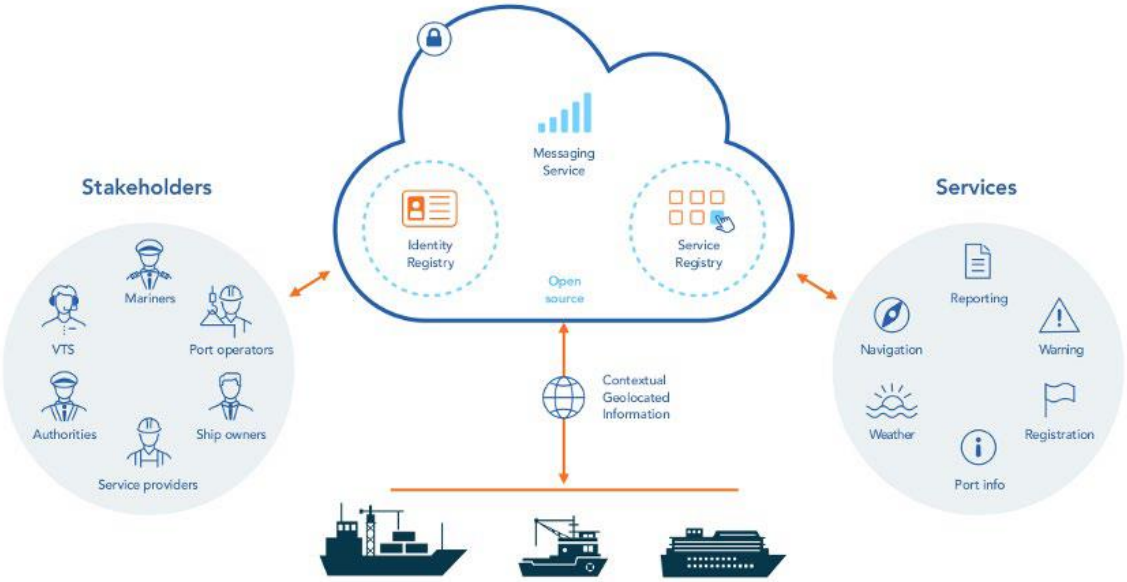


Figure 4-2 Basic Architecture of the MCP

e-Navigation itself covers a wider remit, incorporating the complete end-to-end process of achieving the "harmonisation and standardisation of data communications at sea and ashore for the safety of all mariners and the protection of the marine environment".

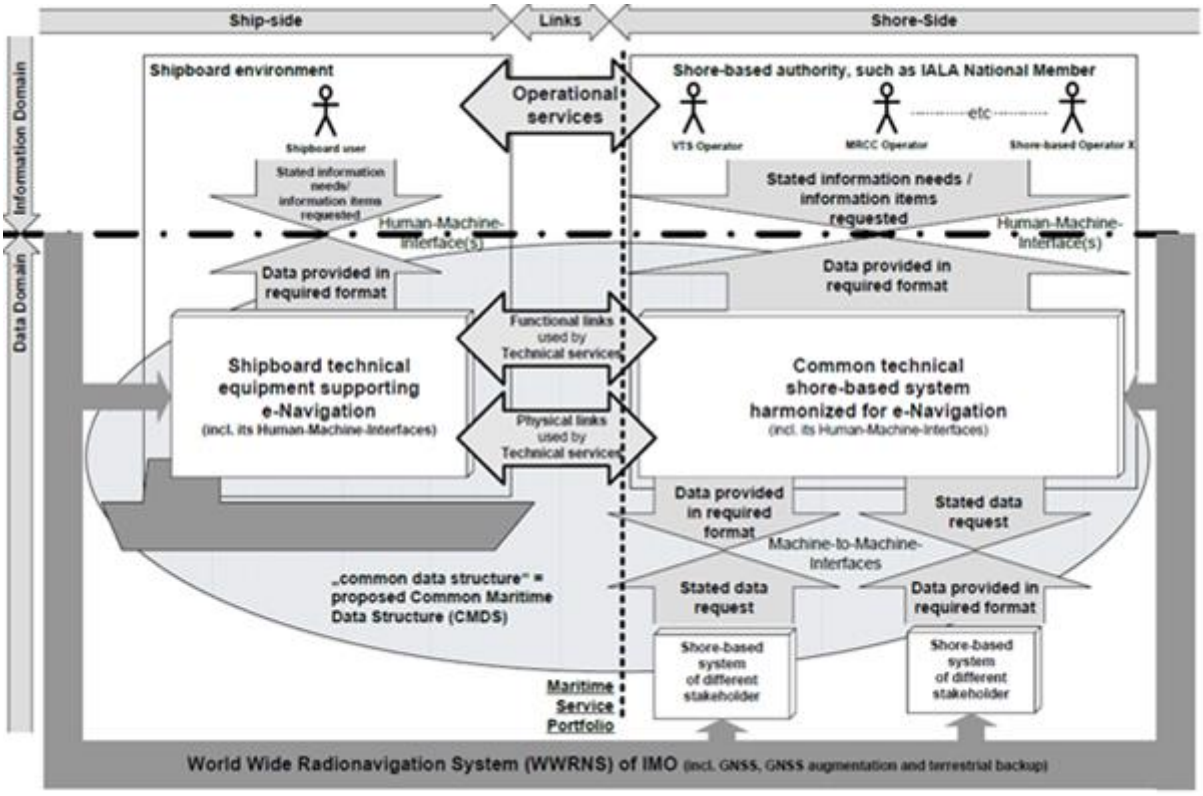


Figure 4-3 *The full remit of e-Navigation covers all maritime communication data. The MCP is an application of this concept to enable delivery of e-Navigation services to maritime users.*

e-Navigation interfaces to INSPIRe in that it supports and enables automated data services from shore-based assets to vessels at sea, however the wider e-Navigation concept is out of the scope of INSPIRe and will not be discussed further.

4.1.5 Archive

The Archive provides a repository for all message types within the DIM System. This includes monitoring and control messages, messages of GNSS measurements and integrity notification messages for dissemination.

The Archive provides a range of non-real time tasks and services. It supports the Performance Monitor and audits of the DIM Service. It provides replay facilities for investigations into events and for future development of algorithm enhancements and ongoing performance improvement.

4.1.6 Performance Monitor

The Performance Monitor assesses the real time integrity determination of the DIM Service against a final truth solution. The truth is provided by IGS final orbits. As such the Performance Monitor does not operate in real time.

The Performance Monitor will evaluate, for each satellite, the projection of the true satellite position and clock error for the worst user location in UK EEZ. Clock errors are considered with respect to the network time of their constellation. The position error is computed in the pseudorange domain as the difference between the satellite position based on broadcast ephemeris (for any live ephemeris), and IGS truth.

The statistical base covers evaluations at 1Hz for around 60 GNSS satellites, so exceeding 2 million samples per day. This is expected to be sufficient to monitor and confirm false alarm rates meet their targets. However, the GNSS service providers are limiting genuine breaches of the GNSS bounds to at most 1 or 2 a year, if any. The missed detection rate of the DIM Service must therefore be evaluated using near misses and DIM modelling in more detail, in order to confirm compliance with the integrity targets.

4.2 DIM Physical Architecture

Figure 4-4 develops a candidate high-level physical system architecture for the integrity monitoring, processing and dissemination system. The architecture includes data flows, the geographic distribution of the infrastructure and the number of redundant components needed to provide resilience and to meet requirements. The principal focus is on the maritime sector.

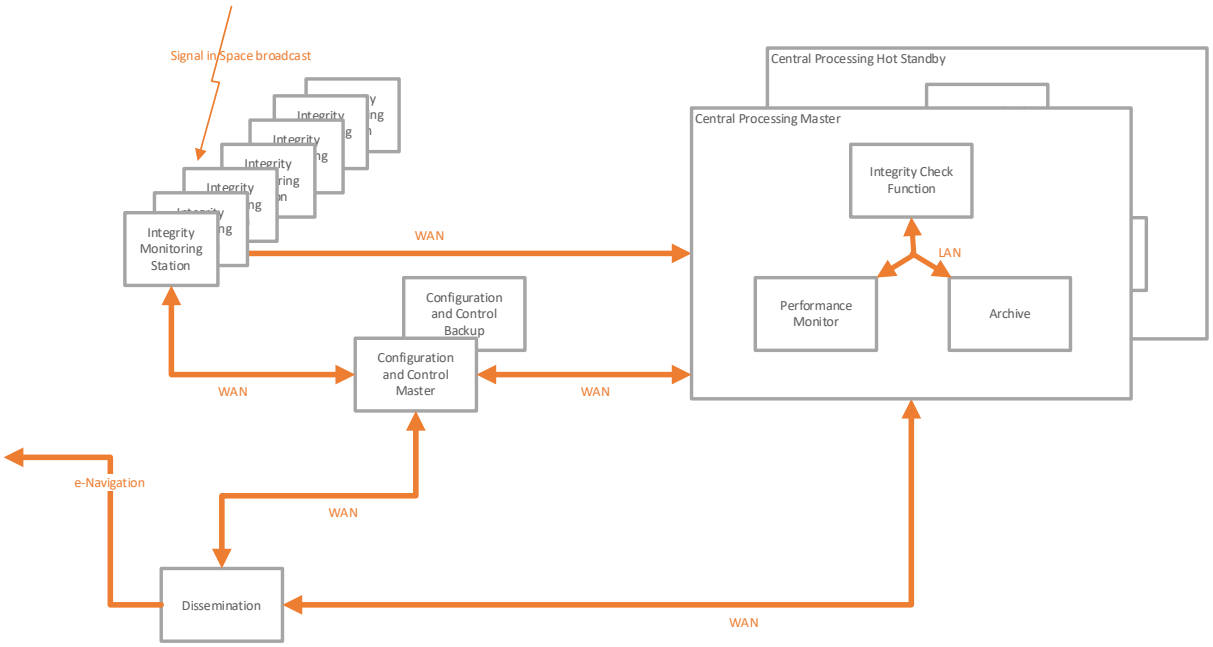


Figure 4-4 High level physical architecture

The physical architecture consists of a distributed network of Integrity Monitoring Stations, two Configuration and Control facilities in master/backup configuration, two Central Processing facilities in hot standby redundant configuration, and a dissemination network with redundancy.

4.2.1 Integrity Monitoring Stations

A network of Integrity Monitoring Stations will be positioned across the UK land mass. The selection of locations will be driven by the need to achieve the greatest achievable geographic spread in order to minimise the geographic dilution of precision within the integrity modelling. The selection of IMS locations will require detailed site surveys, covering their multipath environment and other potential local interference, which are outside the current TN.

For modelling robustness, it is recommended that no three IMS are positioned in a straight line. The total number of IMS shall be chosen such that the DIM System performance requirements will still be met in the event of an outage of two IMS. This will permit a minor network glitch to coincide with routine maintenance. The definitive number and locations of IMS must be supported by RAMS analysis which is outside the scope of the current study. This activity is foreseen within the implementation plan, see section 7.3.1 below. **Figure 4-5** illustrates a network of 7 IMS optimised for geographic distribution but does not constitute a recommendation.

IMS shall maintain a two-way command and monitoring interface with Configuration and Control.

IMS shall transmit GNSS measurement messages at 1Hz frequency containing GNSS measurements at L1 and L5 GPS frequencies, and E1, E5a and E5b Galileo frequencies. Measurements shall furthermore contain quality indicators relating the detection by IMS of cycle slips, multipath, jamming and evil wave forms.

Figure 4-5 Sample Geographical Distribution of IMS

4.2.2 Wide Area Network

A private secure wide area network shall connect the distributed IMS with the central processing facilities, facilitating encrypted communications. Robustness of the WAN shall be

provided through appropriate redundancy. The necessary degree of redundancy and assurance standards will be established through a full RAMS analysis, see section 7.3.1 below.

4.2.3 Configuration and Control

Configuration and Control is responsible for operations planning as well as the deployment, configuration, and operation of the DIM System elements. Configuration and Control periodically solicits monitoring messages of the system state from each real time DIM System element. These are:

- Integrity Monitoring Stations
- Integrity Check Facility
- Dissemination
- Archive

In order to allow for maintenance and unplanned outages two Configuration and Control facilities in master/backup configuration shall be installed. The two Configuration and Control facilities exchange status information to coordinate their control activities.

All interfaces are realised via WAN.

4.2.4 Central Processing

Two central processing facilities shall host the Integrity Check, Archive and Performance Monitoring functions. As detailed in section 3.4.5, GNSS satellites will be monitored on the basis of observations which must have completed a convergence period of around 10 minutes. In order to ensure continuity of the DIM Service, the two Integrity Check facilities shall therefore be connected through WAN and shall configure and operate the real-time Integrity Check functions in hot standby, supporting both switch-over and fail-over functionality.

Planned switch-overs, such as for planned maintenance, will be commanded by Configuration and Control. Unplanned fail-overs to the hot standby Integrity Check Function shall occur automatically in the event of a failure of the active Integrity Check Function. The Dissemination Function shall distribute the master Integrity Check Function's Integrity Notification Message unless it fails to receive this message within a suitable timeout period inside its 1Hz processing cycle.

Each central processing facility shall be protected by an outer security firewall and operate a local area network interconnecting the hosted functions. In addition to the hosted functions and interfaces the central facilities shall interface with a precise timing service and selected external information sources such as IGS.

4.2.4.1 Integrity Check Function

The Integrity Check Function hosts the integrity algorithms and generates the Integrity Notification Message. Section 4.4.2 elaborates the Functional Design of the ICF.

The Integrity Check Function interfaces with Configuration and Control via WAN:

- Receive operational commands and configuration and software downloads as and when required
- Transmit ICF System Monitoring information at 1Hz

The Integrity Check Function interfaces with Integrity Monitoring Stations via WAN:

- Receive messages containing GNSS measurements from up to 12 GPS and up to 12 Galileo channels, comprising code, phase and signal-to-noise measurements, GNSS navigation data, as well as measurement quality information including detected cycle slip, multipath, jamming, evil wave forms at 1Hz frequency, coincident with GPS epochs.

The Integrity Check Function interfaces with Dissemination via WAN:

- Transmit the Integrity Notification Message for dissemination at 1Hz frequency.
- Receive the previous cycle's Integrity Notification Message as received via dissemination self-monitoring at 1Hz frequency.

The Integrity Check Function copies its Integrity Notification Message to the Integrity Check Function of the remote Central Processing Facility via WAN to facilitate checking. Note that the standby Integrity Check Function will only actually check the Integrity Notification Message in the event of switch-over or fail-over.

Requirement [E0090] mandates that the Integrity Notification Message structure shall comply with the NMEA-0183 standard. Based on the standard, each message (sentence) is limited to 82 ASCII characters of which 11 are reserved for message header and checksum. The message would therefore be sufficient to communicate the integrity status 32 GPS and 36 Galileo satellites in a single message, where each satellite is ascribed an 'M', 'N' or 'A' status. The GPS section shall be prefixed 'G', the Galileo section 'E'. The two sections, but not the individual statuses, will be comma separated.

The use of a single message simplifies the design of both the central system and the user navigation solution. Alarms can be communicated without disrupting the message sequence. It is however not expandable beyond 68 monitored GNSS satellites. It would furthermore be dependent on a separate communication warning users that the GNSS status flags are not valid outside UK EEZ. Finally, we note that the NMEA-0183 standard employs a single byte checksum. The fault detection capabilities of a single byte checksum are clearly not in line with the DIM Service integrity requirements.

Whilst the above outline of a message standard demonstrates it may be possible to comply with [E0090], the current study does not propose to do so. Clearly, GNSS ephemeris broadcasts themselves do not comply with NMEA-0183. Furthermore, the NMEA protocol is understood to be designed to govern, and applicable to, wired communication between devices on a vessel, not external e-Navigation communications. In light of the above considerations, the current study proposes to use a binary format with full error detection and correction capability, leaving the navigation processing within the user's terminal responsible for the conversion of the message into NMEA-0183 standard where applicable. The MCP may, as part of its communications protocol, introduce additional wrappers around the core message. However, this would not reduce the responsibility of the Integrity Check Function for the protection of the core message because MCP measures will not be able to detect corruptions of the core message it receives.

4.2.4.2 Archive

The Archive provides a repository for all message types within the DIM System. This includes both monitoring and control messages, real time messages of GNSS measurements and integrity notification messages for dissemination.

Each Archive will collect all WAN messages throughout the operations so that no record transfer will be required in the event of a failover between Central Processing facilities.

4.2.4.3 Performance Monitor

The Performance Monitor assesses the real time integrity determination of the DIM Service against a final truth solution. The truth is provided by IGS final orbits. As such the Performance Monitor does not operate in real time, and operational failover functionality is not provided.

The Performance Monitor retrieves IMS measurement messages (containing GNSS broadcast navigation data) and ICF integrity notification messages from the Archive, as well as GNSS final orbits from the IGS. Performance statistics will be made available to regulatory governance and continuing algorithm evolution by the operator.

4.2.5 Dissemination Function

Two distinct dissemination methods are implemented:

1. Communication of real-time integrity data to the user as an e-Navigation service
2. Issuing navigation warnings via Maritime Safety Information (MSI)

These require two distinct physical architectures, as the communications methods are very different.

4.2.5.1 Dissemination via MSI

Maritime Safety Information (MSI) is a part of the Global Maritime Distress and Safety System (GMDSS) and consists of maritime safety warnings and information pertaining to the safety of life at sea. The system is global, and different maritime authorities have a remit to disseminate MSI over their local area. In the UK, these are disseminated by the Admiralty as Notices to Mariners (NtM) and Radio Navigation Warnings.

NtM are weekly updates of safety-critical navigation information, these consist mainly of long-standing navigational hazards and corrections to published nautical charts.

The Admiralty issues Radio Warnings to fulfil its duty as the UK NAVAREA co-ordinator for the Worldwide Navigational Warning Service (WWNWS), disseminating coastal navigation warnings and alerts. These often relate to objects or people in the water, and events such as severe weather that pose an immediate hazard to navigation.

Radio warnings can be via voice calls from Vessel Traffic Services (VTS) on VHF radio, or broadcast on NAVTEX via medium-frequency radio or satellite. NAVTEX is a remote telegraphy service direct to a physical printer or digital display on the bridge of the ship.

MSI dissemination is not appropriate for the 1Hz Integrity Notification Messages and is instead reserved for infrequent human-readable navigation warnings. A global alert from the DIM, indicating failure of GNSS, or of a single GNSS constellation could be disseminated this way. By contrast, individual satellite alarms have typically a duration of minutes rather than hours, so would likely be communicated only after they expired. Due to the delays inherent in this form of dissemination and the constraint that no ‘not-monitored’ status can be relayed, the user’s RAIM algorithm will also not be able to deduce their instantaneous integrity assurance from an absence of warnings.

The interface between the DIM System and MSI is via e-mail communication with the appropriate NAVAREA co-ordinator, in the case of the UK, in NAVAREA I (North Atlantic) the co-ordinator is the British Admiralty. A working agreement between the DIM operator and the Admiralty is required to ensure timely response to alerts from the monitoring system.

4.2.5.2 Dissemination as an e-Navigation Service

The Maritime Connectivity Platform (MCP) is a conceptual data communications and dissemination platform for sending electronic data between ships and shore-based infrastructure. This data is intended to underpin a number of automated e-Navigation services, able to exchange a wide variety of digital data to and from ship's hardware automatically, and without the mariner's intervention.

The MCP is built upon a number of physical data communications links, any and all of which may be employed interchangeably to facilitate data transfer to and from the ship.

- VHF Data Exchange System (VDES), makes use of a number of marine VHF frequency channels to broadcast data from ship to ship and ship to shore. It builds upon the Automatic Identification system (AIS), which uses VHF to communicate a ship's identity, position and routing information among other data. VDES itself has two forms:
    - Terrestrial: VDE-TER uses two blocks of four adjacent VHF channels for data exchange when within range of VHF communications.
    - Satellite: VDE-SAT uses wider blocks of the VHF band for communications when outside VHF range of a base-station, and for higher bandwidth data backhaul.
- Mobile telecoms. When within range of shore-based conventional LTE (3G, 4G, 5G) data communications transmitters, the vessel will be able to exchange data securely over the internet via IP.
- Satellite telecoms. When outside of coverage of conventional mobile telecoms, the vessel will be able to make use of satellite-based communications. This route induces additional call-and-response (ping) delays and may be unsuitable for some applications.

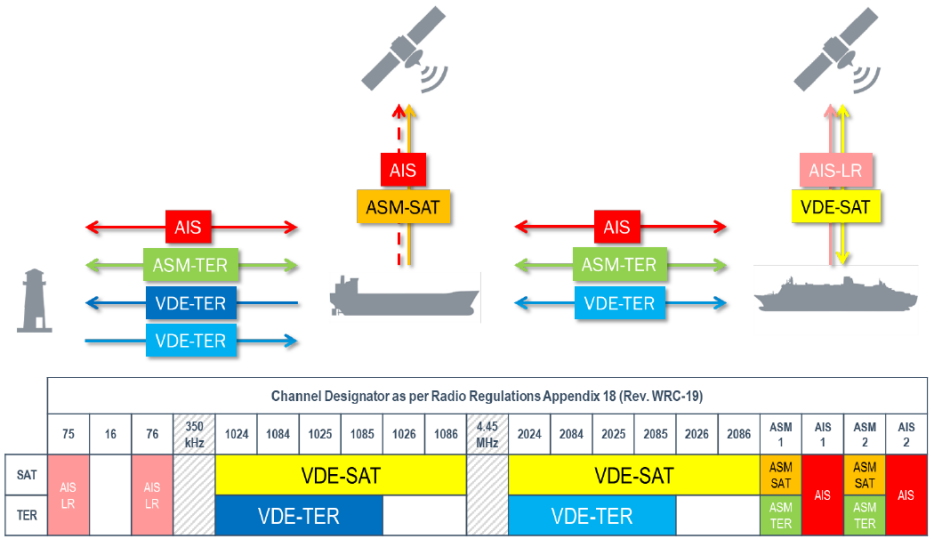


Figure 4-6 The VHF Data Exchange System (VDES)

The physical hardware used for Integrity Notification Message dissemination as an e-Navigation service is simply an IP router to interface the processing centre with the internet. The service must have a MIR entry and also be a registered e-Navigation service with the MSR.

Modified hardware is required on-board the ship to interface to the e-Navigation service, acquire and apply the integrity information broadcast. The communications networks between the service provider and the user's receiver will automatically route and deliver the data.

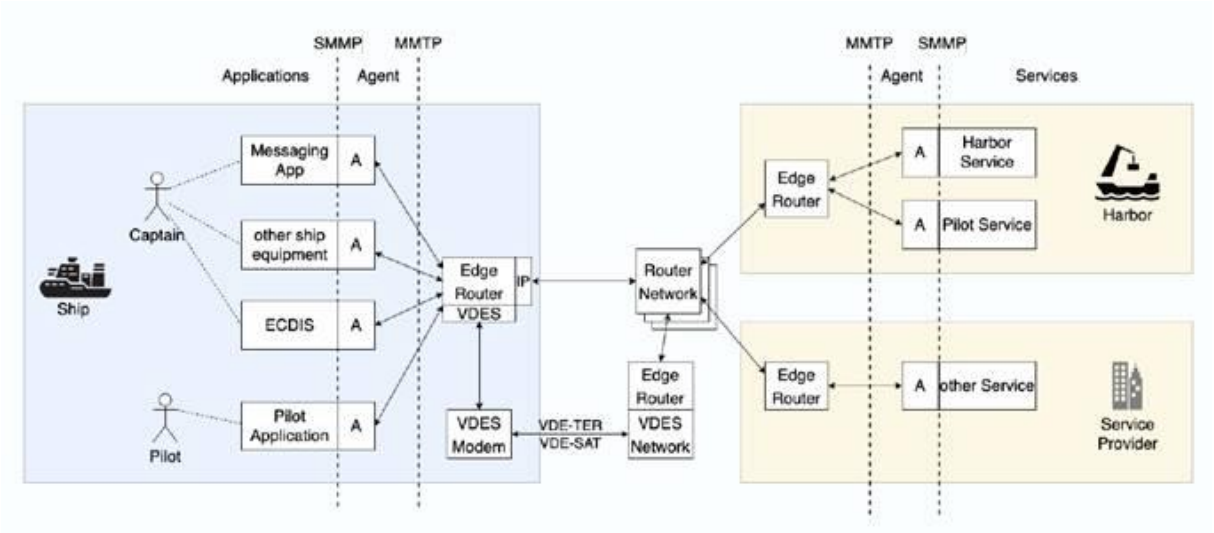


Figure 4-7 e-Navigation Maritime Messaging Service (MMS) Architecture, showing both VDES and conventional mobile telecoms links between a ship and shore-based service providers.

There is some concern over the use of either VDE-SAT or conventional satellite communications (Iridium, or satellite telecoms such as One Web). The issue is that the transportation network may not be able to guarantee a delivery time for the data. This is particularly a problem for VDE-SAT, which operates store-and-forward packet routing and may result in several seconds delay between the integrity data being issued and being applied by the vessel.

Communications via a dedicated VDES link would be the most reliable way to disseminate the data, but this would require the vessel to be within range of a suitably equipped AIS / VDES base station. This may limit reception to within about 20-40NM of the coast and may result in data outages when between stations.

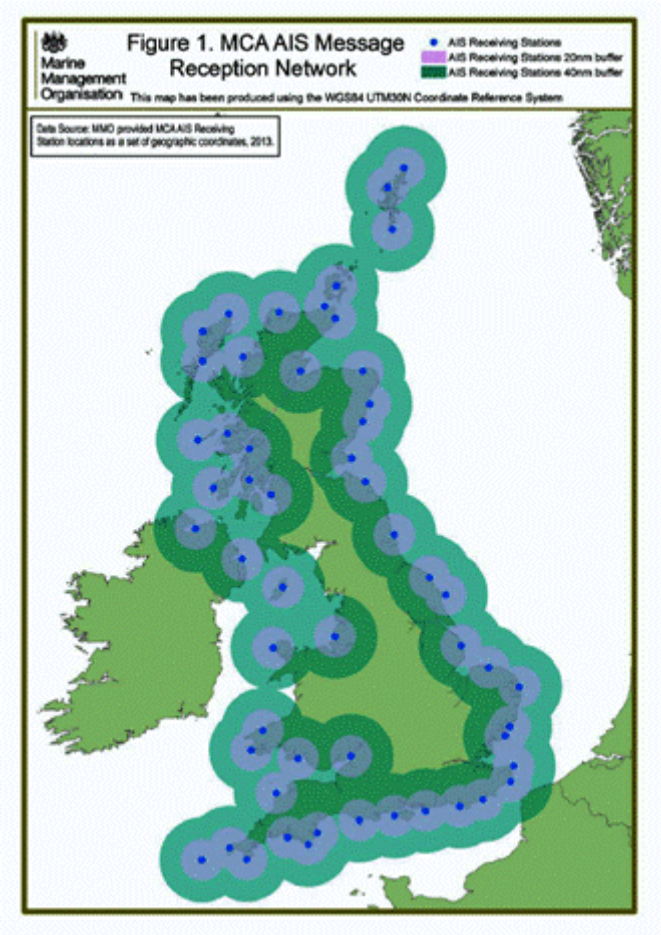


Figure 4-8 Typical data coverage of the existing MCA AIS network.

The future Ocean Phase TTA requirements [CF0190] and [CF0370] may not be fully met by the considered dissemination methods. VDE-SAT is theoretically capable of meeting the requirements, but channel delays may depend on data loading and vessel traffic density. Furthermore, the intermediate carriage is by Internet Protocol. A point-to-point link using VDE-TER will be much more reliable, both in terms of data delivery, and also delay.

4.3 DIM System Synergies With GENS

The GENS Programme [GENS 2022] developed the foundations of the UK's national GNSS event monitoring and incident management capability for the detection, monitoring, effective reporting and recording of PNT interference and disruption.

This section investigates the feasibility of collocating or integrating the DFMC Integrity Monitoring system with the infrastructure and processes proposed for the GENS. It assesses each GENS infrastructure element in terms of available locations, timeliness, frequency, security, safety assurance and robustness, and identifies any gaps against the architecture specifications of the DIM System identified in section 4.2.

4.3.1 Integrity Monitoring Stations

As per [GENS 2022], the GENS system utilises observations of the Ordnance Survey (OS) station network. The OS network comprises of 115 receiver stations in Great Britain, though none in Northern Ireland. The present study focuses on algorithms for measurements sourced from a small number of stations. The study therefore considers synergies when

utilising a small subset, not the entirety of the OS stations. The synergies achievable by accessing a pool of existing real time 1Hz GNSS measurement streams are manifold, considering the significant operational costs of maintaining high specification technical equipment in, by necessity, remote physical locations.

However, the OS measurement products do not meet all a priori requirements established in the specifications of section 4.2 above:

- The assurance of the OS measurement products is at commercial level rather than the higher assurance standard expected for a safety related system.
- OS stations' COTS receivers may not routinely monitor for evil waveforms.
- OS stations' COTS receivers may not meet the robustness and redundancy requirements established in section 4.2 above.
- The unavailability of stations in Northern Ireland reduces the width of the geographical base and thus increases the GDOP experienced by the integrity algorithms.

The preliminary security and safety requirements placed on DIM System elements in section 4.2 above are in line with other safety of life GNSS services. In order to be able to relax these requirements, a full RAMS and security assessment of the DIM System with clearly identified and quantified mitigations will need to be performed. The full RAMS analysis is not expected to prohibit the use of COTS per se but will place requirements on any selected COTS to meet a clearly defined assurance standards (such as DAL C in recent comparable SBAS development). The full RAMS analysis and safety case are beyond the scope of the current study.

Concerning the alternative of using large numbers of the 115 OS stations we must recognise that the 115 OS stations are not homogenous but of varied equipment characteristics. This includes the selection of tracked E5 signals, clock steering, multipath and overall quality. Using a significant subset of the 115 stations would therefore be more akin to opportunistic sourcing. The inevitable geographic proximity between stations would require a very different algorithmic approach, such as protecting against correlated errors, or resonances in Kalman filters.

4.3.2 Wide Area Network

The OS Net observations are distributed via NTRIP. This is an enhanced HTTP internet protocol. Authentication and encryption of the OS messages are not currently employed by GENS. The communication of measurement messages will utilise infrastructure developed and maintained to commercial assurance standard.

The synergies achievable by using existing communications facilities are manifold, considering the significant operational costs of maintaining private wide area networks to remote geographic locations.

As for the receiver stations considered in section 4.3.1, the level of assurance of the network falls below the specifications established in section 4.2 above. Any sharing of infrastructure will require that safety and security mitigations are put in place in the central processing facility, or that commercial networks are upgraded to meet required standards. The full RAMS analysis and safety case are beyond the scope of the current study.

4.3.3 Configuration and Control

GENS and INSPIRe share very similar concepts of operational control, redundancy, switching and failover processes. The sharing of configuration and control facilities should therefore be explored. The GENS central processing facility is developed within a restricted

classified environment with robustness and failover redundancy built in. Therefore, the combined capital and operational expenditure savings of shared physical infrastructure may significantly outweigh the cost of any constraints the INSPIRe needs may place on the design of the GENS system.

4.3.4 Central Processing

The detailed applications and algorithms differ between the GENS and INSPIRe central processing facilities. Synergies are expected to be limited to their hosting.

4.3.5 Dissemination

GENS generates and distributes alerts to critical national infrastructure, and to general users via a web portal. The target audience for INSPIRe is very different so that a sharing of dissemination mechanisms or infrastructure does not appear appropriate.

4.3.6 Conclusion

Functionally, the GENS monitoring stations and wide area network exhibit a significant commonality with the needs of the INSPIRe DIM Service.

However, the GENS Service provides information to its users with very different levels of assurance and integrity compared to the DIM Service. The security and development assurance specifications of the GENS system components and infrastructure are tailored to the level of guarantee given by GENS and are not in line with those of a safety related DIM Service.

It will therefore only be possible to realise synergies if a new safety and security model can be developed for the overall DIM Service and DIM System in particular which differs from the (SBAS inspired) preliminary allocations of section 4.2. This may be explored in a future phase pf the INSPIRe programme.

4.4 DIM Functional Design

This section develops an outline functional design for the main DIM System components, which are the Integrity Monitoring Stations, the Integrity Check Function and Distribution.

4.4.1 Integrity Monitoring Stations

Integrity Monitoring Stations will be deployed across the UK land mass. In addition to the functional elements discussed in **Figure 4-9** below, the IMS design will incorporate non-functional safety and security features. Based on preliminary analysis it will require a development assurance level of DAL C, or a maritime domain equivalent. The remote geographical distribution of the IMS necessitates strict physical and digital security measures.

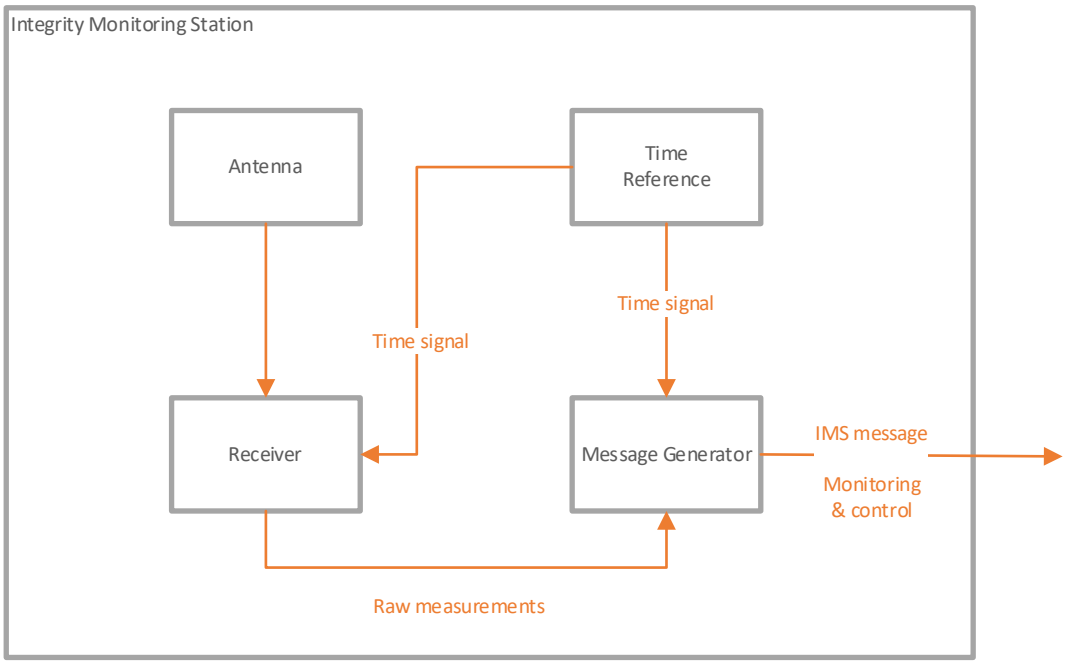


Figure 4-9 Functional Outline of an Integrity Monitoring Station

Module	Description
Antenna	An antenna shielded from multipath
Receiver	GNSS receiver tracking GPS L1 L5 and Galileo E1, E5a and E5b frequencies, with quality indicators including evil waveform.
Time Reference	An atomic clock, a frequency standard for the receiver which will furthermore aid synchronisation between message generator computer and receiver.
Message Generator	A processor converting the raw measurements into the IMS measurement message and distributing it via the WAN. The processor furthermore interfaces with Configuration and Control.

4.4.2 Integrity Check Function

The Integrity Check Function will be a real-time embedded system. Based on preliminary analysis it will require a development assurance level of DAL B, or a maritime domain equivalent. This will constrain the selection of hardware and software platforms, and necessitate the incorporation into the design of additional, non-functional elements such as periodic self-checks of the system, as well as space and time separation of functionalities unsuited to DAL B.

Figure 4-10 shows the real time monitoring and control support layer of the Integrity Modelling within the Integrity Check Function. The modules are described in **Table 6-1** below.

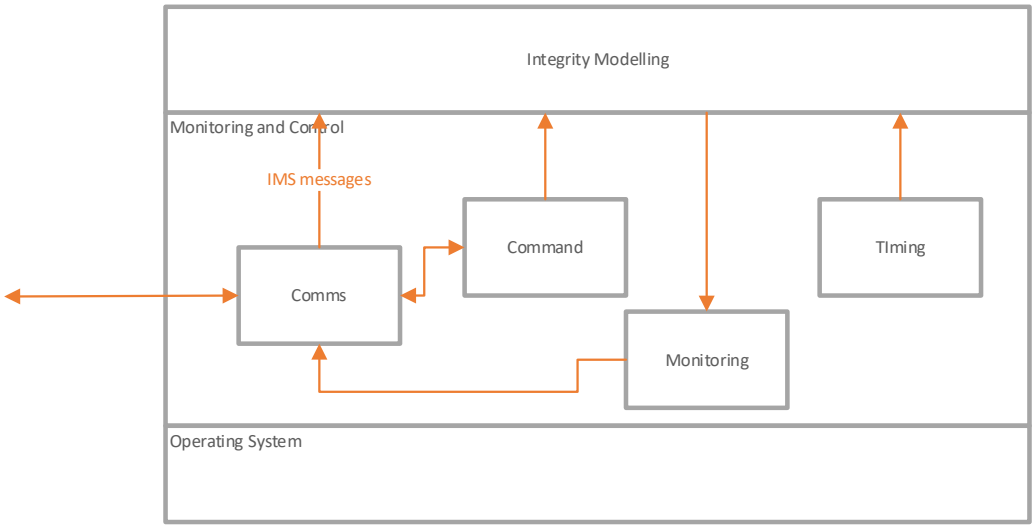


Figure 4-10 Functional Outline of the Integrity Check Function

Figure 4-11 shows the workflow of the Integrity Modelling and the key data entities. The workflow will be performed for each supported ionosphere-free combination of frequencies and for all live ephemerides.

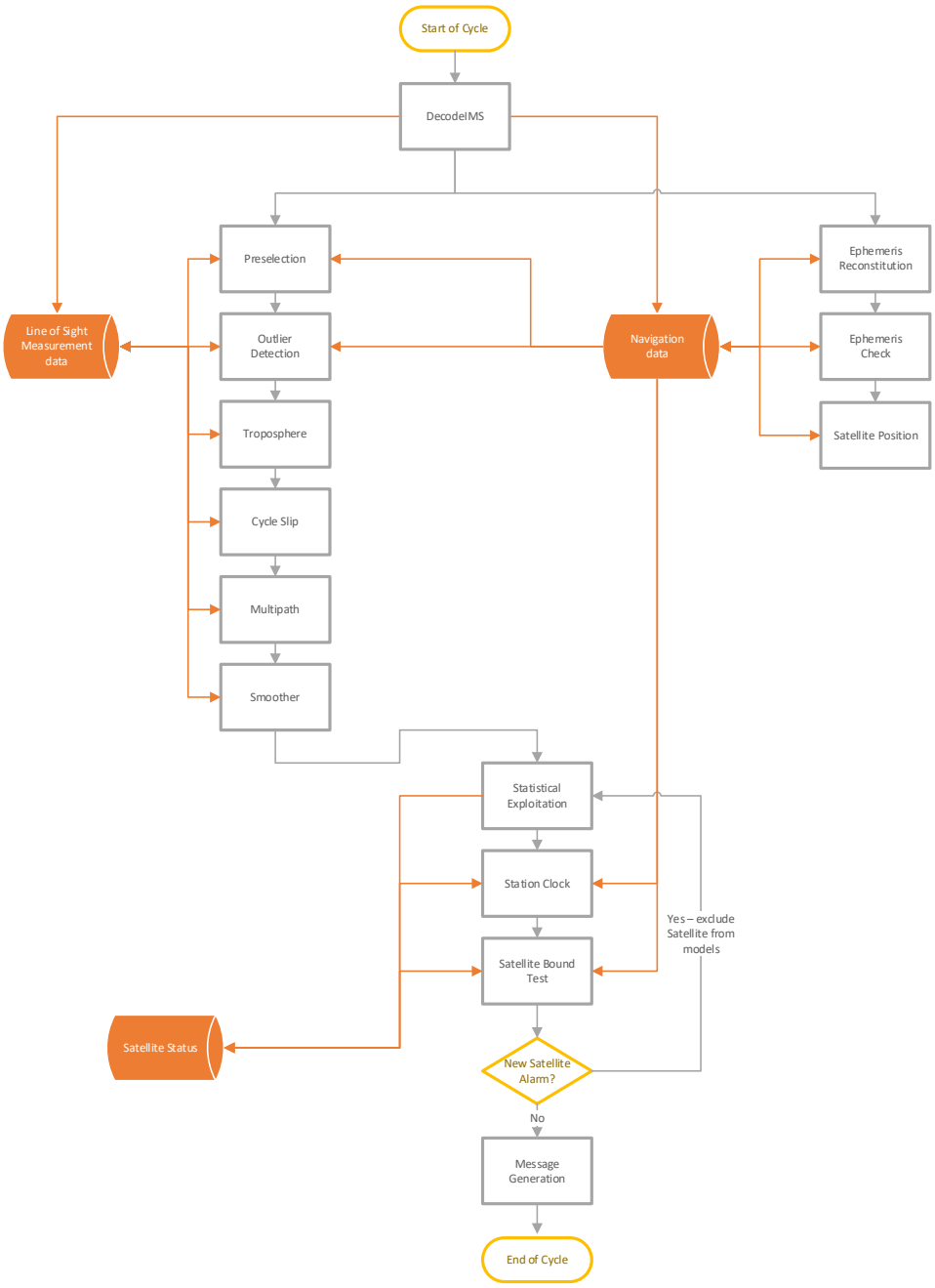


Figure 4-11 Functional Outline of Integrity Modelling

Module	Description
DecodeIMS	Decodes the 1Hz measurement messages received from IMS and stores the raw measurements, IMS quality flags, and navigation data in dedicated data stores for further processing.
EphemerisReconstitution	Assembles the GNSS ephemerides from the sequences of navigation data blocks received, applying consistency checks to eliminate misattributions.
EphemerisCheck	Validates the content of a received GNSS ephemeris concerning format compliance, parameter bounds, health status and consistency with all previous live (i.e., not yet timed out) ephemerides of the same satellite.
SatellitePosition	Computes GNSS satellite positions at a given measurement transmission time for all live ephemerides of the satellite.

Module	Description
Preselection	Excludes measurements if IMS quality information indicates local tracking issues such as multipath or jamming, or signal to noise ratio falls below a minimum, elevation dependent threshold.
OutlierDetection	Forms time series of code and phase observations in order to identify and flag anomalies in the measurement series of the individual line of sight.
Troposphere	Applies tropospheric corrections according to the Saastamoinen model.
CycleSlip	Applies two cycle slip tests, a third order difference model and a dual frequency geometry free combination model in order to detect and disambiguate cycle slips.
Multipath	Passes cycle slip free measurement series through a multipath filter in order to detect any significant multipath.
Smoother	Passes the ionosphere-free combination of pseudoranges through a dual frequency hatch filter, using dual frequency phase measurements, to compute the fully corrected measured pseudorange, which is the ionosphere-free carrier smoothed code.
StatisticalExploitation	Reviews the entirety of flags raised on measurement series per individual line of sight. Attributes fault to GNSS satellites or IMS stations based on statistically significant majorities of lines of sight.
StationClock	Models the station clocks pertaining to each constellation on the basis of the fully corrected measured pseudorange error residuals of the GNSS satellites, using a second order polynomial interpolation over a suitably selected sliding window.
SatelliteBound Test	Performs the final integrity test for each GNSS satellite on the basis of the sample of the fully corrected measured pseudoranges, covering all live ephemerides and ionofree combinations.
MessageGeneration	Constructs the Integrity Notification Message reporting the final satellite status (MON, NM, DU). All statuses are communicated each epoch.
Timing	Manages the synchronisation of the ICF through an interface with an exact time source.
Commands	Handles the commands received from the Configuration and Control Function.
Monitoring	Collates ICF system monitoring information of the ICF for onward transmission to the Configuration and Control facility.
Comms	Handles all external communications of the ICF, via WAN, LAN and dedicated time interface.

Table 4-1 Module Dictionary

4.4.3 Dissemination

The functional specification for dissemination of integrity data as an e-Navigation service is essentially an authenticated public-private-key transmission of data via internet protocol (IP). Whether this is communicated to the vessel directly via satellite or mobile telecoms, or using a VDES link, the basic communications architecture is the same:

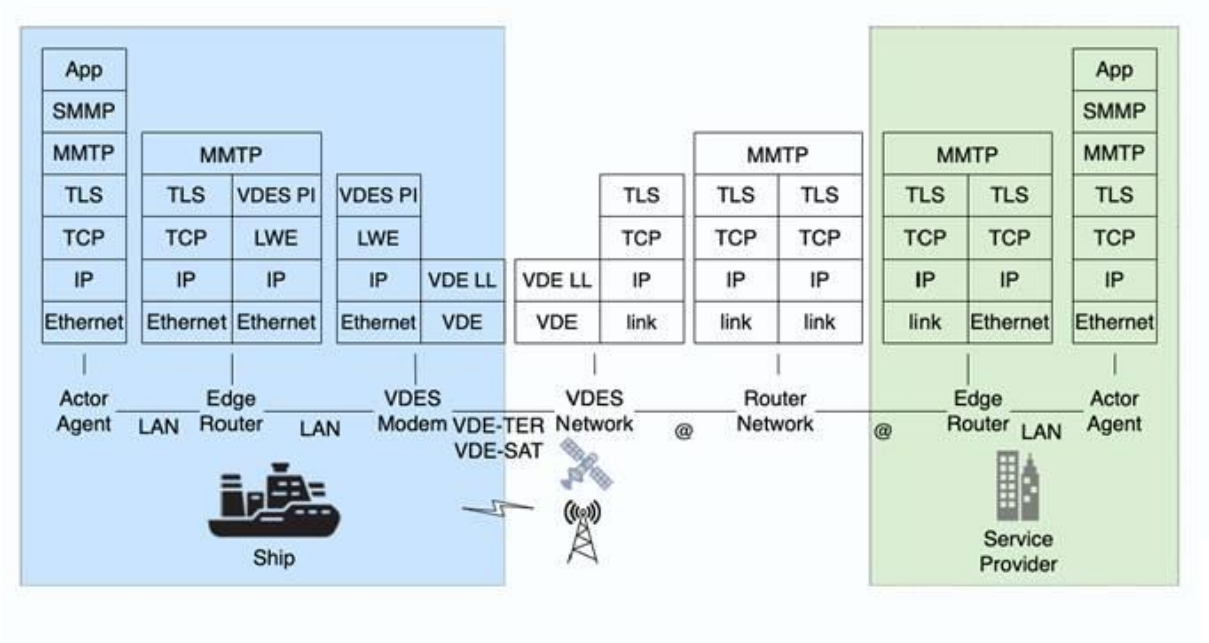


Figure 4-12 Example protocol stack for MMS interface between a service provider and a ship-based user, employing VDES (TER or SAT) link.

Several additional functional processes are involved in the e-Navigation, principally those of the two other aspects of the MCP – the Maritime Identity Registry and the Maritime Services Registry.

4.4.3.1 Maritime Identity Registry

The MIR records the unique identity of every entity (ship, device, organisation or service provider) that will access the MCP. It also provides the public key infrastructure (PKI) for a system of public-private-key cryptography to ensure data messages are authenticated, and end-to-end encrypted.

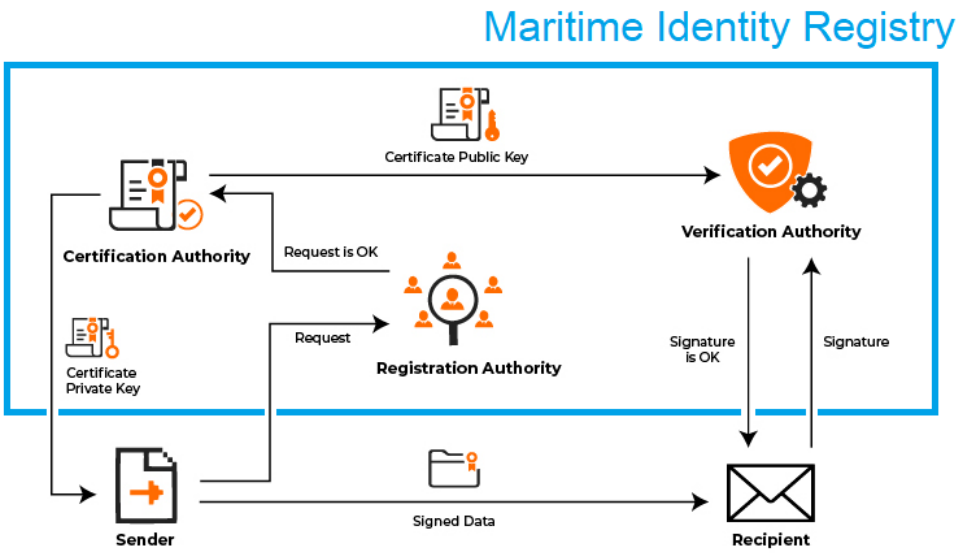


Figure 4-13 Basic public key infrastructure, showing MIR boundary

The functional operation of the MIR is out of the scope of this project, and it will not be described in full. It interfaces to the DIM Service, the “Sender” in **Figure 4-13** by providing private key certification, and also the public key infrastructure for the user, the “Recipient” in **Figure 4-13** to verify the authenticity of the broadcast data.

4.4.3.2 Maritime Service Registry

The MSR provides descriptions of the various e-Navigation services that are available to the mariner in both human and machine-readable formats. It is effectively a phone book, or portfolio of available services, open to the users of the MCP to discover and to which they may subscribe. It also includes machine-readable service specifications that detail how the e-Navigation service functions, and how the required data is broadcast and managed [IALA guideline 1128]. Three main parts of the service description are as follows:

1. **Specification**: A technology-agnostic description of a service on a logical level
2. **Technical Design**: A description of the technology-bound, actual realization of a service on a technical level.
3. **Instance**: Information about the actual URI and other relevant data about a specific running service instance.

The DIM user will access the MSR to obtain this information in order to establish an instance of the integrity data provision service it describes. This access will also be via the identity registry, and end-to-end encrypted for security.

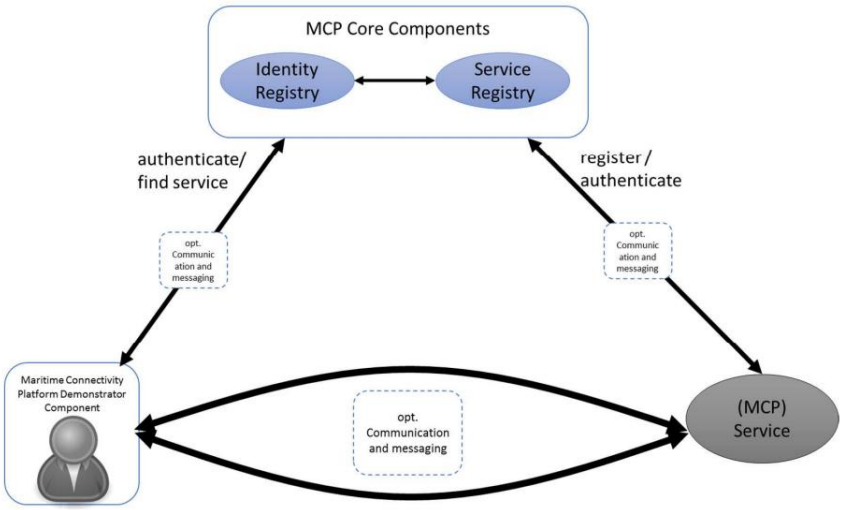


Figure 4-14 Basic functional design of an MCP user accessing an e-navigation service.

This report will not go into further details of the functional aspects of the MSR, since this is strictly out of scope of the INSPIRe project. More details of the operation of the three components of the MCP can be found in the Efficiensea2 website: (https://efficiensea2.org)

5 DIM PROOF OF CONCEPT TESTBED

This section presents the Proof-of-Concept (PoC) Testbed of the DIM System created under WP 7.4 of the INSPIRe Programme. The PoC Testbed consists of a main PoC Processor, a range of supporting tools and both real and synthetic test data.

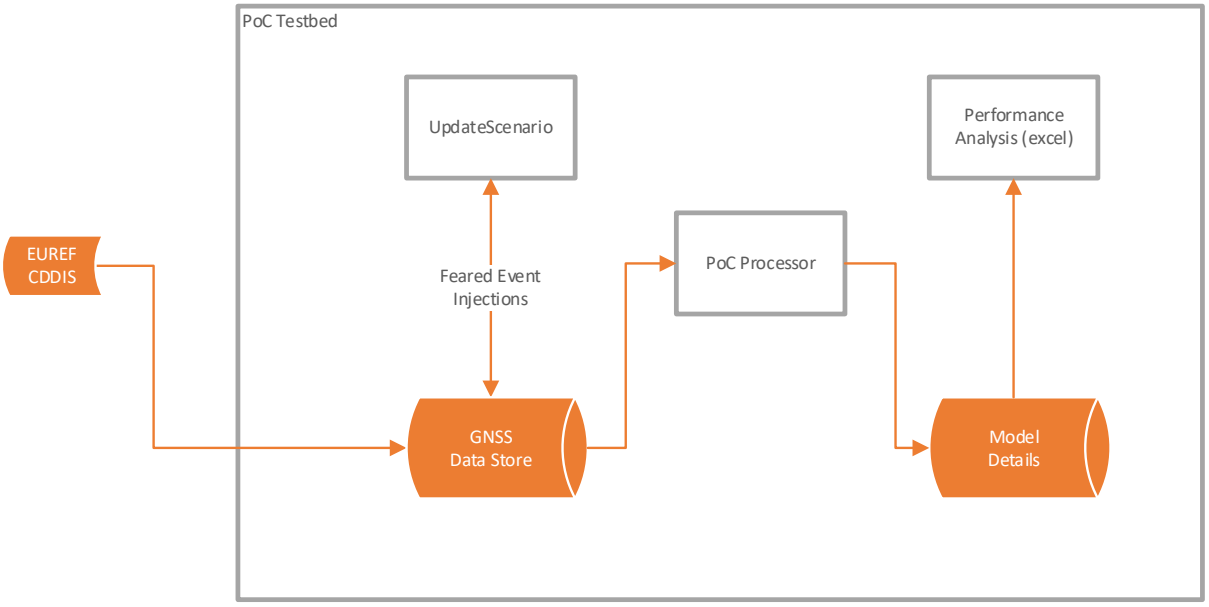


Figure 5-1 Elements of the PoC Testbed

Test data are manually retrieved from the public archives of EUREF and CDDIS. A tool is available to inject a variety of feared event satellite and station fault conditions. The main PoC Processor simulates key algorithms of the DIM System and records details of its modelling for post run performance analysis.

5.1 PoC Processor

The PoC Processor simulates algorithms which are considered of interest to the DIM System. In keeping with its proof-of-concept character, the PoC Processor does not establish end-to-end processing or representative interfaces. The PoC Processor focuses on the needs of performance evaluation and extrapolation.

5.1.1 Scope

The scope of the PoC Processor is driven by the PoC Testbed's objective of performance characterisation. The PoC Processor selects a subset of the processing of the Central Processing of the DIM System only. No IMS processing is being simulated.

An algorithm of the processing model specified in section 3.4 will be part of the PoC Processor if and only if it contributes to the performance characterisation of the DIM System. By contrast, algorithms which purely reflect interfaces or binary choices, are not represented in the PoC Processor or Testbed. This applies to:

- IMS – Processor interfaces; GNSS observations and GNSS navigation message data are taken directly from RINEX files. As a result, the following sub-algorithms are bypassed:
    - Decoding of observation and ephemerides;

    - Validation of ephemeris content with regard to GNSS ICD compliance and satellite health (binary);
    - IMS evil wave form detection;
    - IMS exclusion of measurements based on quality assurance such as multipath, signal to noise ratio, jammer detection;
    - Robustness to IMS misattribution of measurements.
- Equally, the PoC Processor does not construct any outgoing integrity notification message, nor check its good reception by Dissemination, nor apply the extension in duration of user alarms beyond the actual satellite fault. Performance is established on the basis of satellite status.
- The PoC Testbed only models one dual frequency combination per constellation (GPS L1-L5, Galileo E1-E5).
- The PoC Processor evaluates the satellite status only on the basis of the latest valid ephemeris, not any earlier ephemerides which may not yet have timed out.
- The PoC Processor can be configured for GPS and Galileo, but not both simultaneously.
- For the determination of the worst user location the precise UK EEZ has been approximated as a pentagon: (47N,11W), (60N,15W), (65N,0), (56N,4E), (51N,3E) to get the maximum pseudorange error across UK EEZ.
- The PoC Testbed defines the worst observable error as the largest geometric error at any contributing measurement station location.

The scope of the PoC Processor includes both the bias and geometry inversion models of the satellite error.

5.1.2 Specification

5.1.2.1 Interfaces

The PoC Processor shall process:

- RINEX 3.04 GNSS OBSERVATION DATA from GPS and Galileo constellations from at least seven configured measurement stations;
- RINEX 3.04 GNSS NAV DATA from GPS and Galileo constellations;
- SP3 MGEX orbit and clock solutions.

The PoC Processor shall output the following model data to .csv files:

- Final satellite status for each epoch and satellite of the constellation, distinguishing:
    - Not observed by any station
    - Not monitored whilst observed, due to insufficient data or inconclusive modelling
    - Monitored
    - Alarm
- Measurement SNR and multipath per frequency, and satellite elevation
- Details of the residual between true and measured range for each observation (subject to converged line of sight)
- Satellite range error at worst location in UK EEZ, and at worst EUREF / IGS station location
- Details of the final satellite model, including mean bias, alarm threshold, number of contributing observations.

5.1.2.2 Functional

The PoC Processor shall, for the configured time period, process the configured observation, navigation and truth data. The algorithmic processing chain shall comprise SatellitePosition, Preselection, OutlierDetection, Troposphere, CycleSlip, Multipath, Smoothing, StatisticalExploitation, StationClock and SatelliteBoundTest algorithms as per algorithm processing model section 3.4.

5.1.3 Architecture

Figure 5-2 presents the top-level architecture of the PoC Processor.

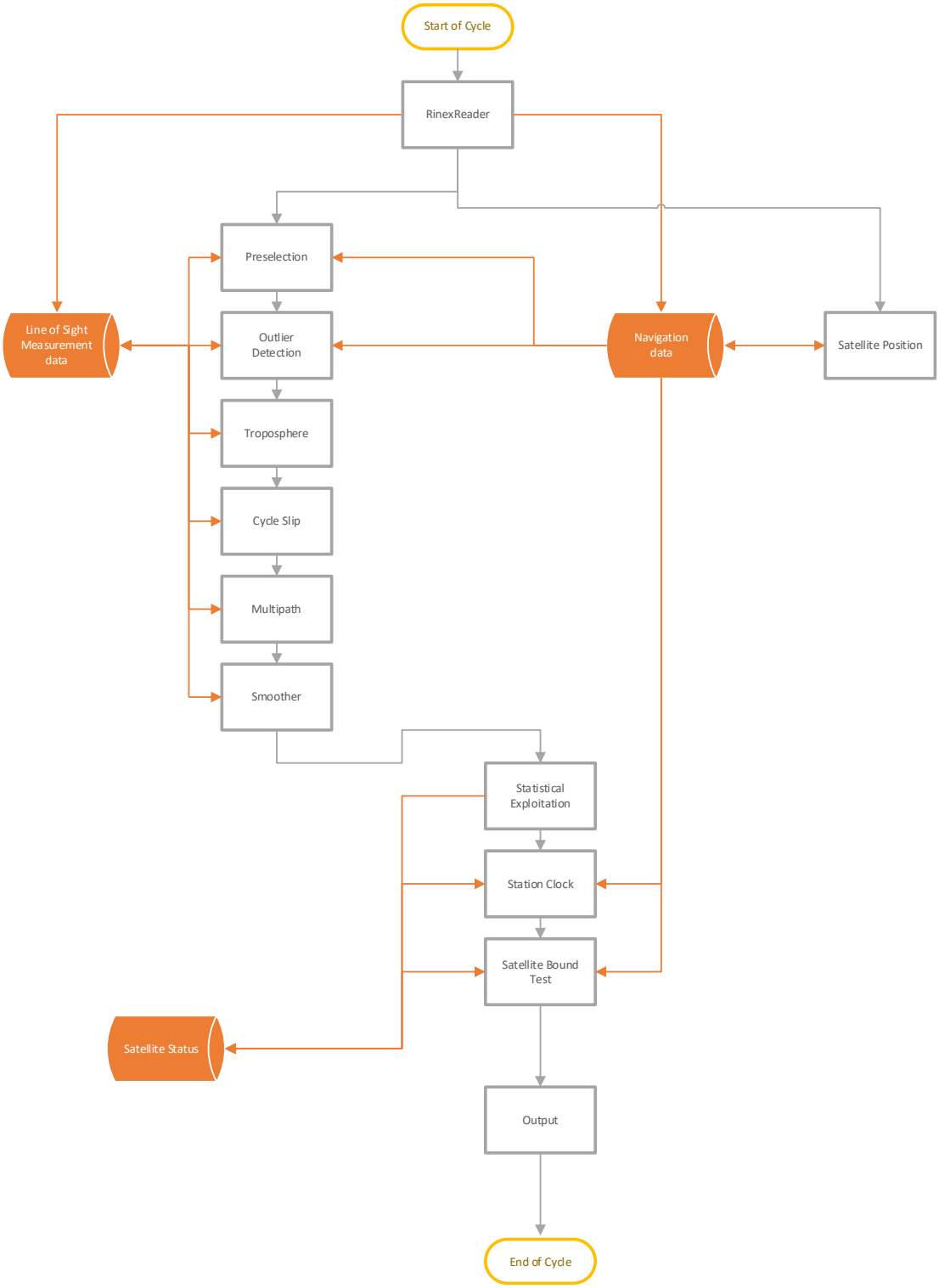


Figure 5-2 Functional Outline of PoC Processor

Table 5-1 contains the module dictionary.

Module	Description
RinexReader	Reads the observation and ephemeris files in RINEX 3.04 format, as well as the IGS truth solutions in SP3 format.

Module	Description
SatellitePosition	Computes GNSS satellite positions at a given measurement transmission time for all live ephemerides of the satellite. The module also computes the true errors based on comparison against the IGS truth.
Preselection	Excludes measurements if signal to noise ratio falls below a minimum, elevation dependent threshold.
OutlierDetection	Forms time series of code and phase observations in order to identify and flag anomalies in the measurement series of the individual line of sight.
Troposphere	Applies tropospheric corrections according to the Saastamoinen model.
CycleSlip	Applies two cycle slip tests, a third order difference model and a dual frequency geometry free combination model in order to detect and disambiguate cycle slips.
Multipath	Passes cycle slip free measurement series through a multipath filter in order to detect any significant multipath.
Smoother	Passes the ionosphere-free combination of pseudoranges through a dual frequency hatch filter, using dual frequency phase measurements, to compute the fully corrected measured pseudorange, which is the ionosphere-free carrier smoothed code.
StatisticalExploitation	Reviews the entirety of flags raised on measurement series per individual line of sight. Attributes fault to GNSS satellites or IMS stations based on statistically significant majorities of lines of sight.
StationClock	Models the station clocks pertaining to each constellation on the basis of the fully corrected measured pseudorange error residuals of the GNSS satellites, using a second order polynomial interpolation over a suitably selected sliding window.
SatelliteBound Test	Performs the final integrity test for each GNSS satellite on the basis of the sample of the fully corrected measured pseudoranges, the latest ephemeris and ionofree combinations. Two models, as per algorithm specification are implemented and can be selected via configuration. The baseline model (“mean”) uses the average of the observed residuals, the alternative model (“geometry inversion”) inverts the observation geometry matrix to compute a 4-d error estimate.
Output	Resulting satellite statuses, residuals and model details are recorded in .csv files for subsequent performance analysis.

Table 5-1 Module Dictionary

5.1.3.1 Inter-frequency Biases

With the exception of GPS L1/L2 P(Y) users, satellite inter-frequency biases, TGD (GPS Timing Group Delay) or BGD (Galileo Broadcast Group Delay), must be accounted for. To this end, the PoC Testbed to uses fixed Differential Code Biases (DCBs) as published by CDDIS in their DCB.BSX product. We note that for greater autonomy, the Galileo ephemeris does provide BGDs. Due to the slow changing nature of inter-frequency biases, these were not considered required for the PoC Testbed.

The application of DCBs is specific to the exact signal traced. For example, DCBs of C1C_C5X and C1C_C5Q have the potential of being significantly different.

Concerning the IMS stations, the DIM algorithm only processes dual frequency ionofree combinations. For a given constellation, each IMS observation will experience the same combination of signals so that the encountered receiver hardware inter-frequency bias will be

indistinguishable from, and indeed absorbed into, the receiver clock bias. Therefore, the station inter-frequency bias does not require to be modelled separately.

5.1.4 Verification

The PoC Processor has been verified through use.

5.2 Injection Tool

The UpdateScenario tool allows a range of feared event conditions to be injected into observations in RINEX format.

5.2.1 Specification

The tool processes RINEX 3.04 GNSS OBSERVATION DATA files. The tool executes commands of a command file to modify GNSS observations using the following command syntax:

- `command, startdate, station, constellation, prn, signal, duration, magnitude`

Where **`command`** provides the observable and type of perturbation in the following format:

- `set_<clock/range/phase>_<bias/drift/wobble>`

Here **`clock`** instructs to modify both range and phase, ensuring consistency between range (in meters) and phase (in cycles). **`range`** instructs to modify only the pseudorange measurement, **`phase`** only the carrier phase measurement.

`bias` instructs to offset the numerical value of the observable by a constant offset. Note that a 'bias' command necessarily creates two signal jumps, one at the start and one at the end of the fault injection.

`drift` injects offsets of magnitude following a sine wave through 180 degrees, ensuring no signal jumps are created in the process. Therefore, the maximum offset during the duration of drift will be reached at the mid-point of the interval, and the initial slope of the drift will be π * magnitude / duration.

`wobble` instructs to employ the `rand()` function to generate random offsets for each cycle.

`startdate` represents the first cycle during which the specified condition shall be injected. It is formatted 'yyyy, mm, dd, hh, mm, dd'.

`station` identifies the measurement station. Recognised values are DARE, ENIS, HERS, INVR, LICC, NTGM and SHOE, see section 5.4 below. No wildcard value exists for stations because different stations will be contained in different RINEX files. Where multiple stations should be impacted, multiple commands will be given.

`constellation` identifies the constellation to be modified. Recognised values are 'G' for GPS and 'E' for Galileo only.

`prn` identifies the PRN number within the selected constellation. Valid parameters range from 1-32 for GPS, and 1-36 for Galileo. A wildcard '99' will modify all satellites of the selected constellation.

`signal` identifies the signal to be modified. 1 for GPS L1 or Galileo E1, 5 for GPS L5 or Galileo E5 (RINEX code C8* or L8*). A wildcard '99' modifies both frequencies. Phases will be adjusted consistently accounting for wavelength.

duration represents the duration of the event in seconds.

magnitude represents the magnitude of the offsets in meters. In the case of phase modifications, the offset in cycles will be computed from offset in meters and applicable wavelength. In the case of a drift, magnitude represents the maximum magnitude reached at the midpoint of modification. In the case of a wobble, the random offset will be between +/- magnitude.

Example:

- `set_clock_bias, 2021, 02, 07, 02, 05, 00, DARE, E, 33, 99, 3600, 5,`

Where a measurement is missing from the RINEX file, the UpdateScenario tool shall leave the field unchanged.

The specification of the UpdateScenario tool excludes facilities to inject faults into the RINEX 3.04 NAVIGATION DATA files. The volume of required injections did not justify the development of specific functionality. Instead, ephemeris errors must be injected manually into the ephemeris archived files. Ephemeris injections are defined through the magnitude of change to the Kepler parameter. The resulting 4-d position error and the observable pseudorange error will vary with time and location, and are derived.

Using the command set, the feared events, satellite and station faults identified in section 3.3 and [INS Thr] can be injected into an existing GNSS data set as follows:

User:

- **Category 1**
  - Satellite clock jump: set_clock_bias with identical magnitude for all stations
  - Satellite clock drift: set_clock_drift with identical magnitude for all stations
  - Bad ephemeris: manually adjust one ephemeris entry in navigation data file
  - Signal corruption: set_phase_drift with identical magnitude for all stations, for code carrier divergence
- **Category 2**
  - Multiple satellite fault: As above for all subcases of Category 1, but simultaneously for multiple satellites
- **Category 3**
  - Whole constellation fault: As per section 3.2.1, not all whole constellation faults conditions are detectable in the DIM System. Detectable types of error can be simulated through the simultaneous injection of conditions into all satellites of a constellation.

IMS station

- Station clock jump: set_clock_bias for single station but all satellites
- Station clock instability: not simulated because sufficiently represented in raw data
- ISB: As per section 3.2.1, hardware ISB and GGTO cannot be detected within the DIM System, but would require additional monitoring against absolute time reference.
- Multipath: not simulated because sufficiently represented in raw data
- Cycle slips: set_phase_bias for single station, single satellite, single signal
- Scintillation: set_phase_wobble for single station, single satellite, single signal to generate epoch by epoch phase noise representing phase scintillation; amplitude scintillation is not modelled
- Jamming and Spoofing: not simulated because these are currently out of scope of the INSPIRe project

- Data Gaps: not simulated because sufficiently represented in raw data
- Misattribution: not simulated because the detection is a logical binary decision which does not impact performance
- False Lock: set_phase_drift for single station, single satellite, single signal.

5.2.2 High Level Architecture

The UpdateScenario functionality consists of:

- RINEX Reader, to read RINEX 3.04 OBSERVATION data
- Command processor, to update each individual observation RINEX line as and when applicable and to log each modification performed.

5.2.3 Verification

The UpdateScenario tool is verified by inspection of its logs, updated RINEX files and indirectly by the responses of the PoC Processor algorithms to the injected conditions.

5.3 Evaluation Tools

The PoC Processor routinely calculates and records in its output those residual errors which are subsequently needed for performance evaluation. The errors are:

- The actual 4-d ephemeris error, defined as the difference between ITRF truth position and satellite clock bias as derived from the IGS SP3 solution, and the instantaneous position and clock computation based on the applicable satellite ephemeris.
- The pseudorange error for each observer (IMS or applicable UK EEZ user location), defined as the sum of the projection of the true satellite position error projected onto the line of sight of the observer and the true satellite clock error:

$$PseudorangeError = \begin{pmatrix} x_{sat} - x_{obs} \\ y_{sat} - y_{obs} \\ z_{sat} - z_{obs} \end{pmatrix} * \begin{pmatrix} \Delta x_{sat} \\ \Delta y_{sat} \\ \Delta z_{sat} \end{pmatrix} - \Delta t_{sat}$$

IGS SP3 truths are available at 5-minute intervals. The PoC Processor does not perform a full polynomial interpolation for intermediate times due to the smooth linear nature in which the errors evolve. Refer to section 5.4.4 for special considerations regarding the clock truth.

Spreadsheets are then used to compare the algorithmically modelled bias, sample variance and alarm test thresholds against the true projected pseudorange errors, and to aggregate the individual observations into statistics of availability, false alarm probability and missed detection probability.

The information recorded by the PoC Processor is also used to confirm the algorithmic response to injected feared event fault conditions. The process of verifying responses to feared events has not been automated because of the complexity and variability of the relevant criteria and indicators for each condition.

5.4 Test Data

The INSPIRe study has selected a set of test data based on the twin objectives that test data should be as representative of the DIM System processing as possible and that test data

should be based on observations of real signal in space, minimising the contributions of synthetic data at this early proof-of-concept stage.

5.4.1 UK Data Selection

The key representativity criteria of any test data are as follows:

- Data must be available at 1Hz frequency because algorithms are constructed for this frequency.
- Stations must have external clock steering for stability of measurements.
- Station locations must cover the full geographic spread of the UK.
- Based on theoretical analysis, at least 7 stations should be available.
- The data archive should have uninterrupted data for at least one week.
- The exact tracked L5 and E5 signals should be consistent between all selected stations.
- Station sites must be proofed against multipath to the maximum extent possible.

Initial inspection of potential data archives established that the above criteria are unachievable. The most comprehensive archive, EUREF, maintains data from 6 UK stations: DARE, ENIS, HERS, INVR, LICC, SHOE. Two of these, HERS and LICC, are part of the IGS network of stations, but only HERS possesses external clock steering. In addition, CGI obtained data from a GMV receiver in Nottingham, which will be referred to as NTGM.

The inclusion of ENIS (Enniskillen) data was highly desirable in order to create a more comprehensive geographic cover of the UK but it did constrain the time window to February 2021 because EUREF archives are online for only 2 years, and ENIS ceased its contributions to EUREF March 2021.

Ideally, the exact same signals should be processed from each station. Whilst for the L1/E1 frequency the C1C and L1C signals are consistently available, this is not case for the L5/E5 frequencies because stations track subsets of Cnx and Lnx where $n \in \{5,6,7,8\}$ and $x \in \{C,Q,X\}$. The PoC Testbed has selected the C8Q, L8Q and C8X, L8X signals as the least diverse sources. Note that ‘8’ constitutes a combination of E5a and E5b, neither E5a nor E5b are consistently tracked by all stations.

5.4.2 Alternative Data

Given the limited of availability of UK test data the PoC Testbed explored if alternative groups of stations might be available which better meet the representativity criteria. This requires a cluster of at least 7 stations within a 10 by 10-degree latitude / longitude range, similar to the size of the UK land mass. In order to be representative of ionospheric environmental conditions the stations must be in moderate to Northern latitudes.

Whilst there are high concentrations of stations in central Europe, no 10 by 10 grid contained 7 stations with external clock steering and 1Hz data availability. High concentrations of stations in California are located at an unrepresentative latitude. The study hence concluded that the overall representativity of the data set would not be increased by moving to a different geography.

5.4.3 Feared Events

We recall from section 3.5.3 that the non-detection of feared events below their detectable magnitude is nominal behaviour of the DIM algorithms. The PoC Testbed therefore has the twin goals of demonstrating that the feared events can be detected in principle, and to

characterise the approximate minimum detectable magnitude of each type of feared event. In keeping with the proof-of-concept nature, the present study is not able to establish a full distribution of detection probability against event magnitude for each feared event type. Instead, the experimentation typically creates two cases of injection for each feared event type, one below and one above the detectable magnitude to confirm that the error is detected in principle and provide an indication of the detection threshold.

Considering the available data volumes and the resulting maximum numbers of satellites monitored, the experimentation on multiple failures is limited to injections of two simultaneous feared event conditions. The injection and subsequent detection of three or more conditions would not be supported by the volume of observations available. The simulation result would inevitably be a loss of all monitoring and would not be representative of the proposed DIM System. We note that, at the same time, the statistical likelihood of 3 simultaneous faults remains extremely low given the established GPS and Galileo error rates.

As a corollary, feared event experimentation can only be representatively performed during periods of good observability when at least 5 satellites have continuous observations permitting the algorithms to monitor them. This pre-condition is expected to be met continually in any operational DIM System but is not always met in the PoC test data. In particular, it is very rarely met for the GPS constellation due to the fact that only half the current GPS constellation broadcasts L5 signals (16 satellites at the time of the selected test data, see section 6.1.1 for details). The PoC feared event experimentation has therefore been limited to Galileo (with 22 suitable satellites).

For feared events involving a jump of one or more observables to a faulty value we must distinguish between two cases. If the jump occurs whilst the satellite is being observed by the IMS stations, detection may be based on the established time series of observables (section 3.4.2.3). This will typically be more sensitive than the alternative where the jump occurs during a period when the satellite is not observable from any IMS station. Therefore, PoC experimentation simulates both cases of jump.

Equally, feared events involving drifts will experience two detection thresholds. Large drifts will be detectable instantly because they destabilise established time series in DIM algorithms modelling long before the magnitude of the position error prompts a detection. Smaller drifts will accumulate until the resulting position error reaches the alarm threshold. Again, PoC experimentation must cover both magnitudes.

5.4.4 Truth Data Considerations

The assessment of all DIM algorithm performances is critically dependent on the accuracy and relevance of the truth solutions.

5.4.4.1 Position Truths

Constellations and archived data sources use a variety of co-ordinate reference frames. GPS navigation information uses WGS84, Galileo GTRF, SP3 solutions IGb14. However, analysis confirms that differences between the three frames never exceed 3cm so that they are negligible for the purposes of the PoC Testbed. No dedicated coordinate transformations are performed for the experimentation evaluation.

By contrast, EUREF station coordinates expressed in ETRF were converted to ITRF2014 using the EUREF toolset. The station positions provided in RINEX OBSERVATION files are rough approximations and must be disregarded.

Whilst both GPS and Galileo ephemeris positions relate to the Antenna Phase Centre, the SP3 final solutions relate to the satellite’s Centre of Mass. The Antenna Phase Centre Offset

(APCO) from the Centre of Mass is clearly detectable as a position bias in the order of just under 1m. It has therefore been taken into account in the truth computations.

APCOs vary significantly between individual satellites even of the same constellation and block, and between frequencies. IGS14.atx provides APCOs for all Galileo satellites and for GPS Block III. We note however that for GPS Block IIF, no L5 APCOs have been published and that IIF L5 APCOs may differ from IIF L1/L2 APCOs by up to 9cm. This systematic error remains within the PoC Testbed truth and performance evaluations.

The PoC Testbed follows the RTKlib algorithm in order to apply the APCOs to ionofree combinations.

5.4.4.2 Clocks

Unlike position solutions, IGS clock solutions are highly dependent on their chosen reference time frame. Published clock truths frequently differ by 7ns which converts to a 2m range offset. For an example, refer to the GFZ (Potsdam) and COD (Berne) clock truths of Galileo E01 satellite, day 38 of 2021, 00:50: GFZ 0.790701µs, COD 0.797480µs. The differences reflect the different time references to which the solutions will be tied. These time references may be selected from UTC, GPS time, or a global constellation time. The offset between GPS and Galileo network times is being maintained only within the same order of magnitude.

As a result, there is no obvious preferred reference of the satellite clock error. At the same time, an error of 2m magnitude, left unaccounted for, would degrade performances irrecoverably. The PoC Testbed accounts for the reference ambiguity as follows.

The DIM Service user will not be exposed to any abstract UTC, GPS, or Galileo time reference, but to the average of the ensemble of satellite clocks observed by the user at the time of positioning. This average will then be absorbed into the receiver clock error model by the user receiver so that only satellite clock offsets relative to the average impact the integrity of the user solution.

The ‘ideal’ reference time will be user specific and cannot be directly replicated by the DIM System. As an approximation, the PoC Testbed deducts the average of the clock errors of all clocks in use from the residuals, matching both the user receiver and the DIM algorithm behaviour, both for evaluation of individual station pseudorange residuals and for modelled satellite errors. This enables the most accurate assessment of the integrity for the user.

Nevertheless, it remains a concern that the user receiver behaviour when faced with multiple constellation observations is not fully standardised. A user who either applies the receiver clock defined by one constellation to the other or uses a clock offset relating to a mixed constellation will be exposed to errors which have not been monitored by the DIM algorithms.

5.4.4.3 Error Bound

For the purposes of the PoC Testbed, the alarm threshold has been set to 4.42 URA in GPS, or 4.42 SISA in Galileo.

We highlight that, as per [GPS ICD] section 20.3.3.3.1.3, integrity properties of the URA are “*specified with respect to the scaled (multiplied by either 4.42 or 5.73 as appropriate) upper bound values of the URA index (see 20.3.3.1).*” For a URA index of 0, this is 2.4m, for index 1 it is 3.4m. By contrast, the RINEX NAVIGATION DATA records the nominal URA of 2.0m or 2.8m respectively. The PoC maps these values to the integrity bounds accordingly.

Galileo ephemerides are broadcast on two channels, I/NAV and F/NAV. Broadcast ephemerides typically differ in clock parameters but not Kepler. Whilst differences in SISA are theoretically allowed the PoC Testbed has not encountered any. The data source is

identified in RINEX NAVIGATION DATA files. The PoC Testbed uses the parameters of source I/NAV, source equalling 517. This ephemeris contains a complete set of BGDs.

6 DIM PROOF OF CONCEPT EXPERIMENTATION

This section presents the DIM System Experimentation conducted within the Proof-of-Concept (PoC) Testbed under WP 7.5 of the INSPIRe Programme. This section reviews the data quality, specifies the conducted experiments, and reports the analysis and conclusions of the PoC Testbed.

6.1 Station Quality

As a first step, we characterise the volume and quality of data available which drive the subsequent experimentation, algorithmic tuning and conclusion. It justifies the extrapolation applied to some of the results.

6.1.1 Data Volume

Data volumes depend on the numbers of satellites per constellation in orbit which broadcast in the required frequencies.

For GPS, only Block IIF and Block III satellites broadcast the L5 signal. In February 2021, there were 12 Block IIF satellites (PRNs 1, 3, 6, 8, 9, 10, 24, 25, 26, 27, 30, 32) and 4 Block III satellites (PRNs 4, 14, 18, 23), so only a total of 16 satellites, resulting in some coverage gaps. We note that since February 21, only two satellites (PRNs 11 and 28) have joined the L5 providers, so that the available constellation for an L1-L5 dual frequency user now stands at 18 satellites.

For Galileo, 24 satellites were in orbit in February 2021, all of which broadcast the required E1, E5a and E5b signal. However, two satellites, E14 and E18, operate in highly elliptical orbits and cannot be tracked by some receiver types. As a result, they do not reach the minimum number of observations required for DIM algorithm monitoring in the test data. The effective Galileo constellation size was therefore 22.

Inspection of the data archives furthermore revealed a multitude of data gaps, some cases affecting single stations, others affecting all stations of the EUREF archive. These gaps naturally cause a loss of monitoring, and an associated degradation in continuity and availability.

6.1.2 Clock and Phase

The PoC Testbed analysed the carrier phase noise of the raw observations using for simplicity the third order difference of consecutive 1 Hz observations. In the proposed algorithmic model, third order differences exceeding 0.5 phase cycles are considered indicators of cycle slip. **Table 6-1** presents third order differences for GPS L1 frequency measurements, from a small representative sample of measurements. The phase noise appears largely clock driven considering that typically all frequencies and observations from a station exhibit almost identical third order differences.

Station	DARE	ENIS	HERS	INVR	LICC	NTGM	SHOE
3rd order (cycles rms)	0.61	0.19	0.01	0.84	0.12	0.42	0.59

Table 6-1 Examples of Observed Phase Noise

If cycle slip detection was based on a threshold of 0.5 cycles, then the observed noise levels would prevent all subsequent modelling due to lack of continuity in most lines of sight. The PoC Testbed therefore raised the cycle slip detection threshold to 10 cycles, effectively disabling the cycle slip detection. It is evident that this permits genuine cycle slips of

significant magnitude to enter and contaminate subsequent DIM algorithmic models. At the same time, the performance of HERS (the only source with external clock steering) demonstrates that a threshold of 0.5 cycles is entirely consistent with the high quality specification of DIM IMS and therefore appropriate for an operational DIM System.

6.1.3 Multipath

The second significant driver of modelling performance is the presence of multipath. Significant multipath can be observed for all sites with oscillations of the smoothed pseudoranges in the order of 1m to 2m for rising and setting satellites. **Figure 6-1** illustrates the observed behaviour, showing the smoothed pseudorange residual for each station for a pass of GPS PRN 08 on 12/02/2021. For reference, the true ephemeris error is plotted in the bottom right graph.

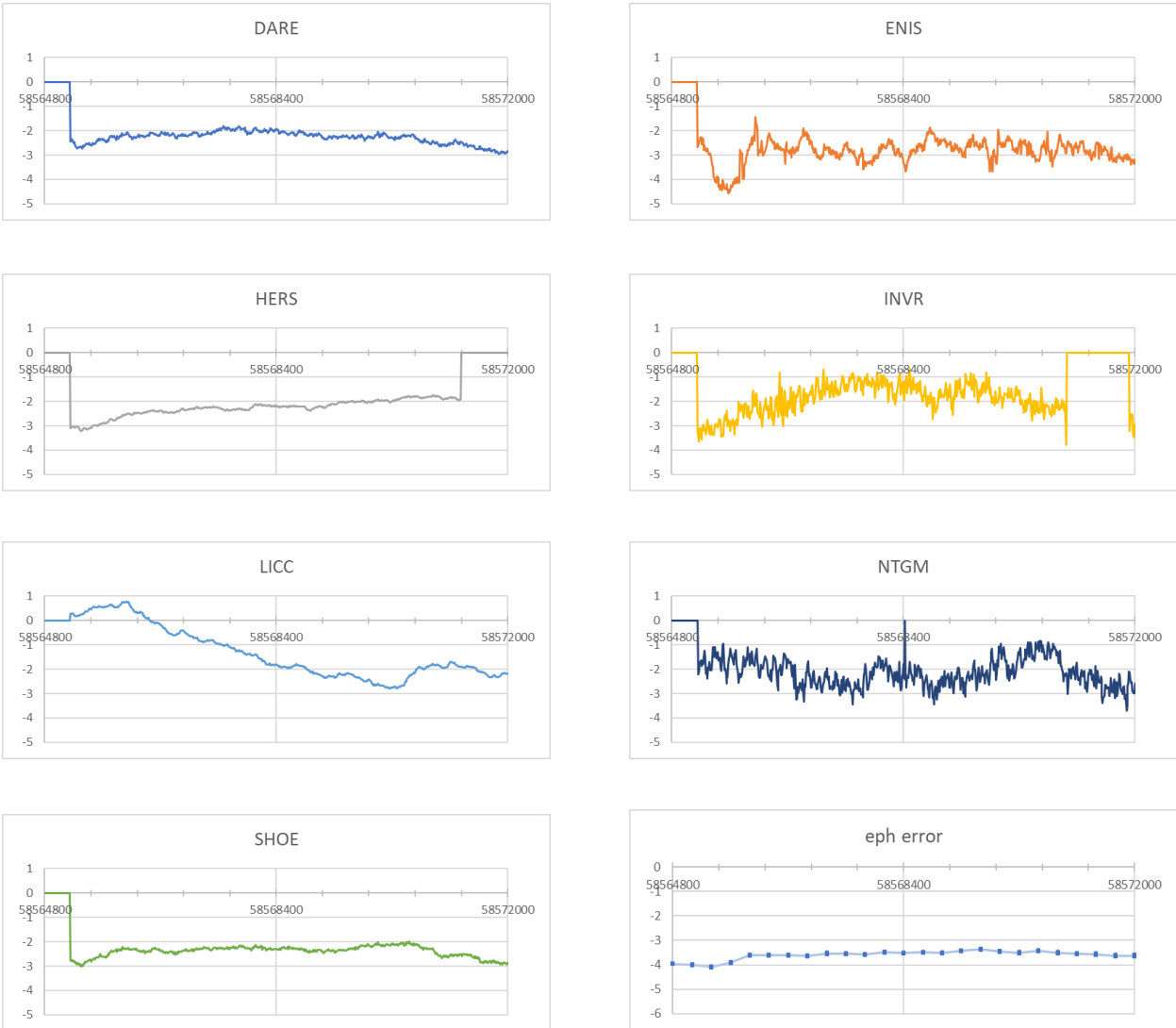


Figure 6-1 Examples of Observed Multipath

A review of the results suggests that the level of carrier phase noise in most stations interferes with the effectiveness of the proposed multipath detection filter. That is to say, multipath for the stable measurement series of HERS is much more reliably detected and quantified than for other stations whose phase noise blunts the filter. This effect occurs even

though the station clock instability should not directly propagate into the code-minus-carrier filter inputs.

At the current levels and with degraded multipath filter effectiveness significant residuals occur for many rising and setting satellites. The PoC Testbed was therefore forced to tighten the multipath detection threshold for low elevation satellites, effectively excluding on grounds of suspicion, rather than clear confirmation.

6.1.4 Station Residual Errors

As identified in section 3.4.5, the key driver of DIM System missed detection and false alarm performance is the distribution of measurement errors impacting the measurement residuals computed by the algorithms. Performance expectations were based on an overbounding σ of 0.4m. Section 3.4.5.6 shows that the variance and distribution of these errors directly impacts the required margin between actual ephemeris error and URA / SISA error bound. The PoC Testbed therefore evaluated the distribution of the pseudorange errors for all stations.

Figure 6-2 to **Figure 6-8** present the discrete and cumulative distributions for the 7 stations, for the Galileo constellation, E1-E5 dual frequency observations. The HQ plot evaluates the subset of measurements whose SNR exceeds 43 for the E1 frequency, and 50 for the E5 frequency. Normal distributions approximating the actuals are included for reference.

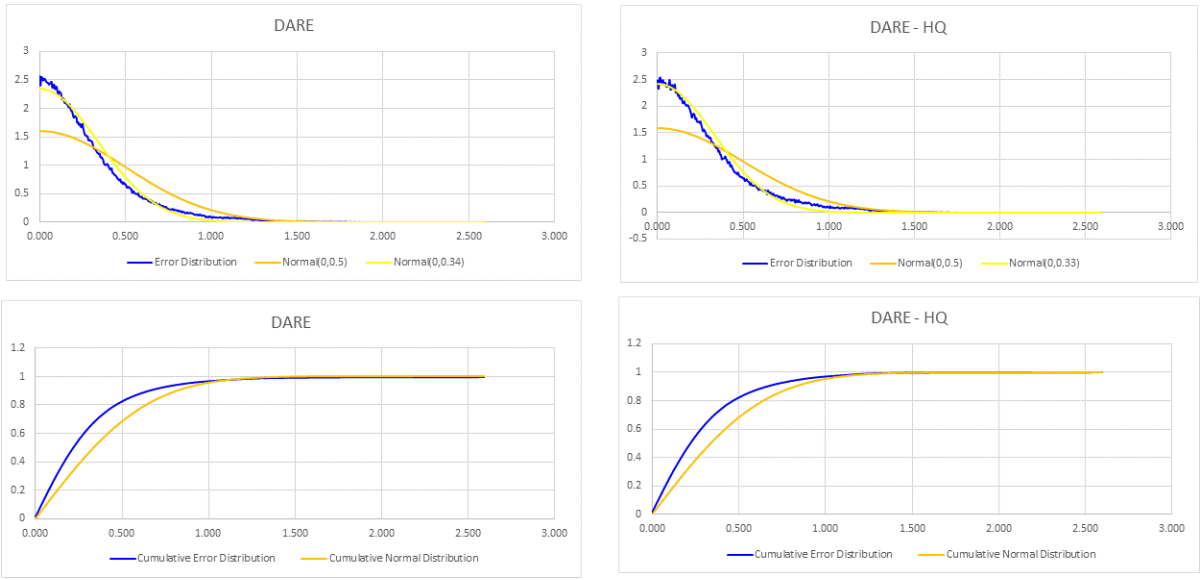


Figure 6-2 Distribution of DARE Measurement Errors, Galileo

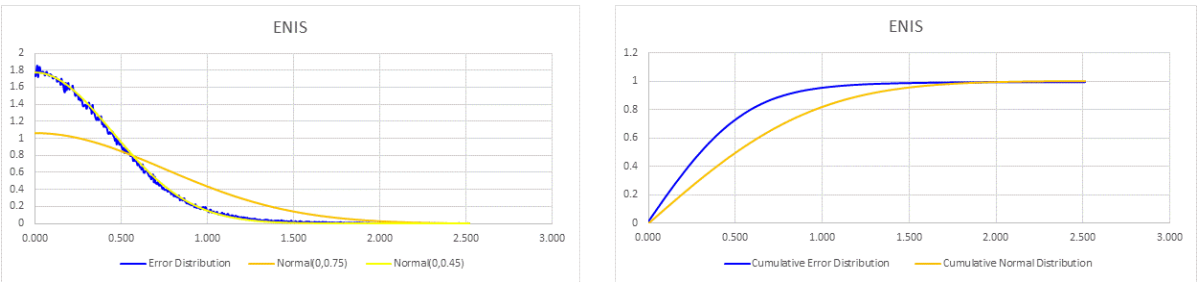


Figure 6-3 Distribution of ENIS Measurement Errors, Galileo

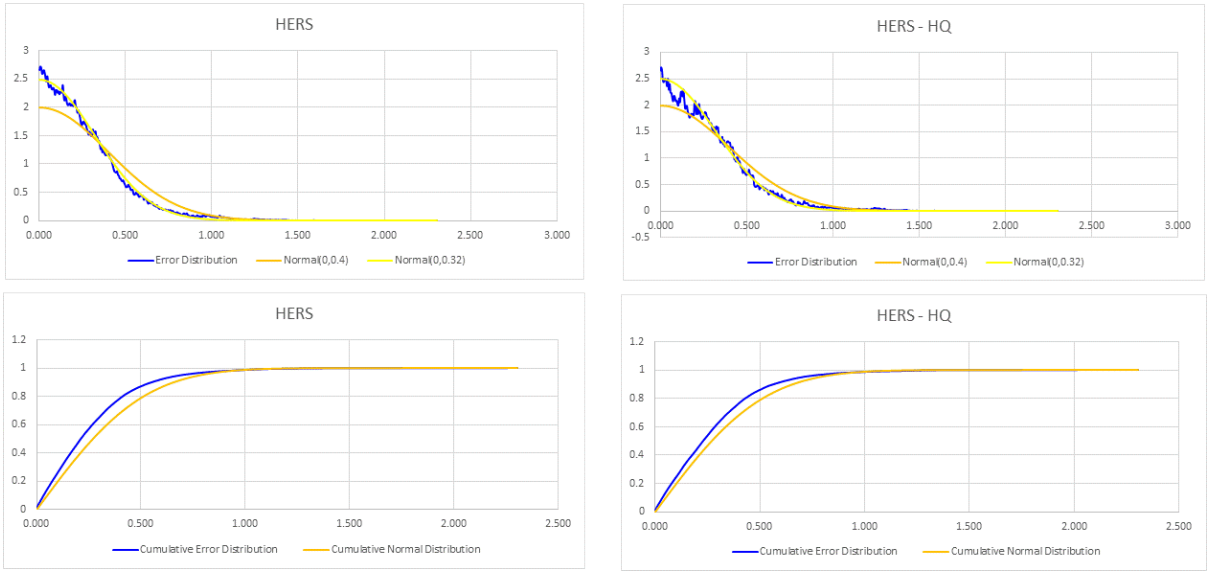


Figure 6-4 Distribution of HERS Measurement Errors, Galileo

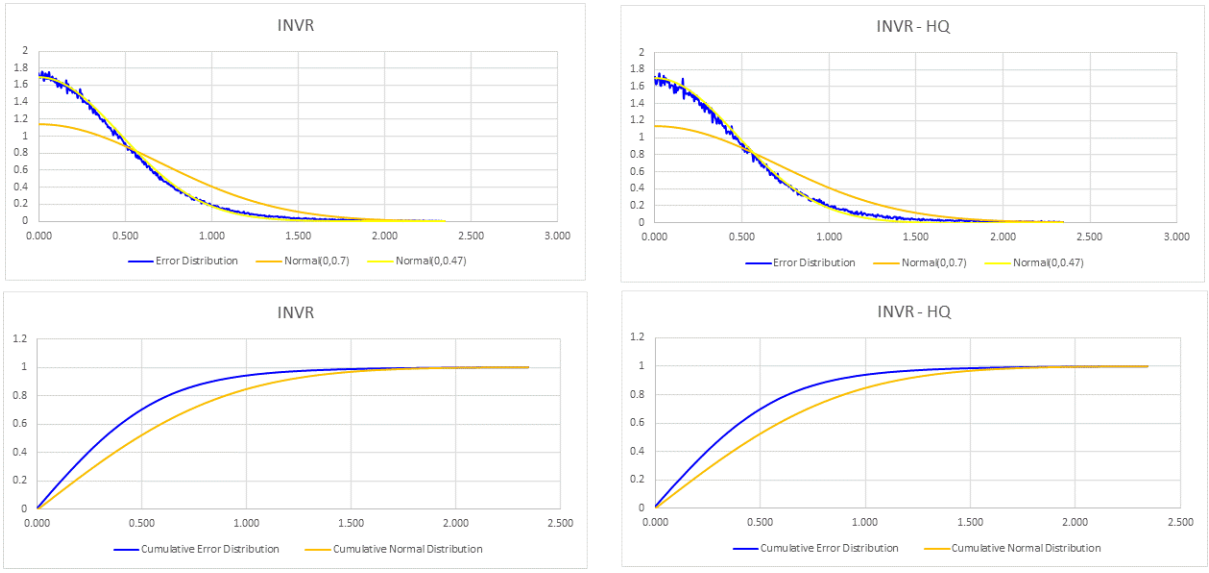


Figure 6-5 Distribution of INVR Measurement Errors, Galileo

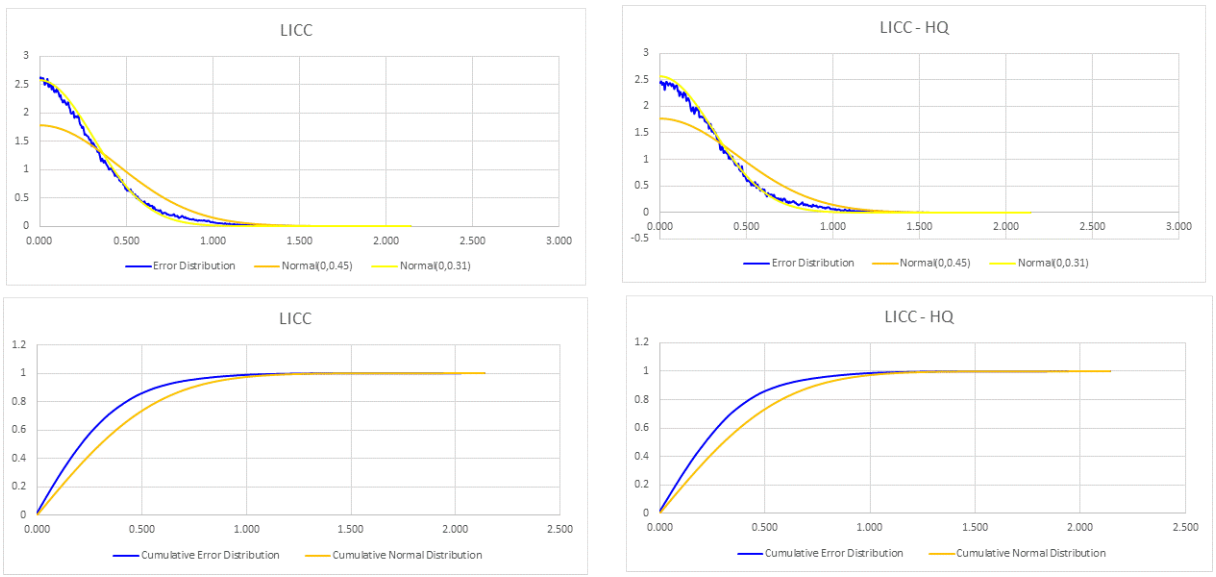


Figure 6-6 Distribution of LICC Measurement Errors, Galileo

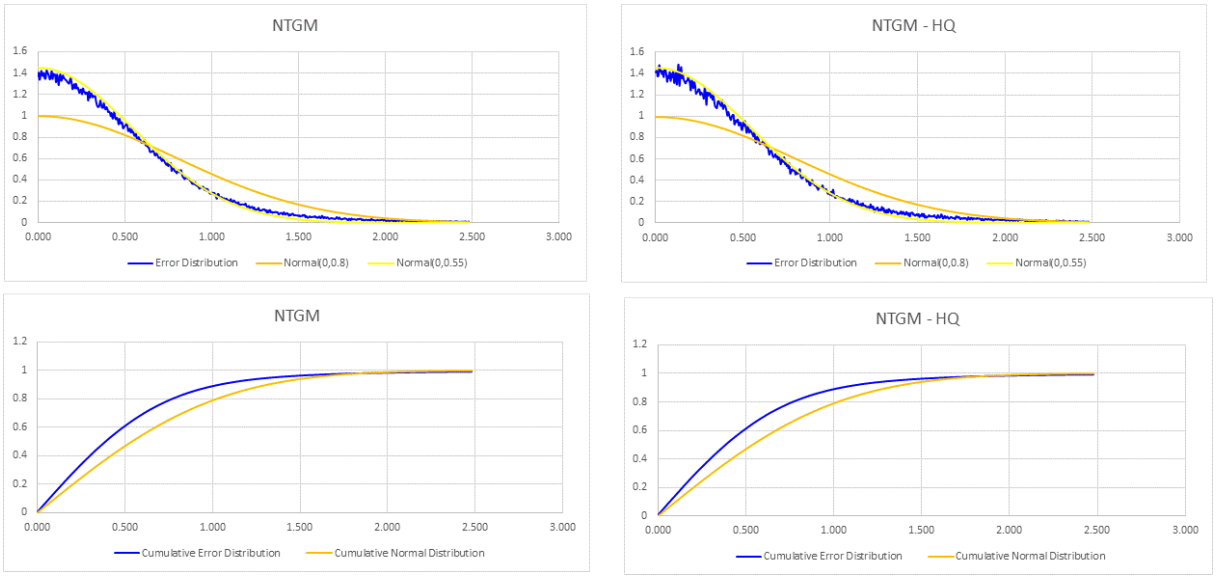


Figure 6-7 Distribution of NTGM Measurement Errors, Galileo

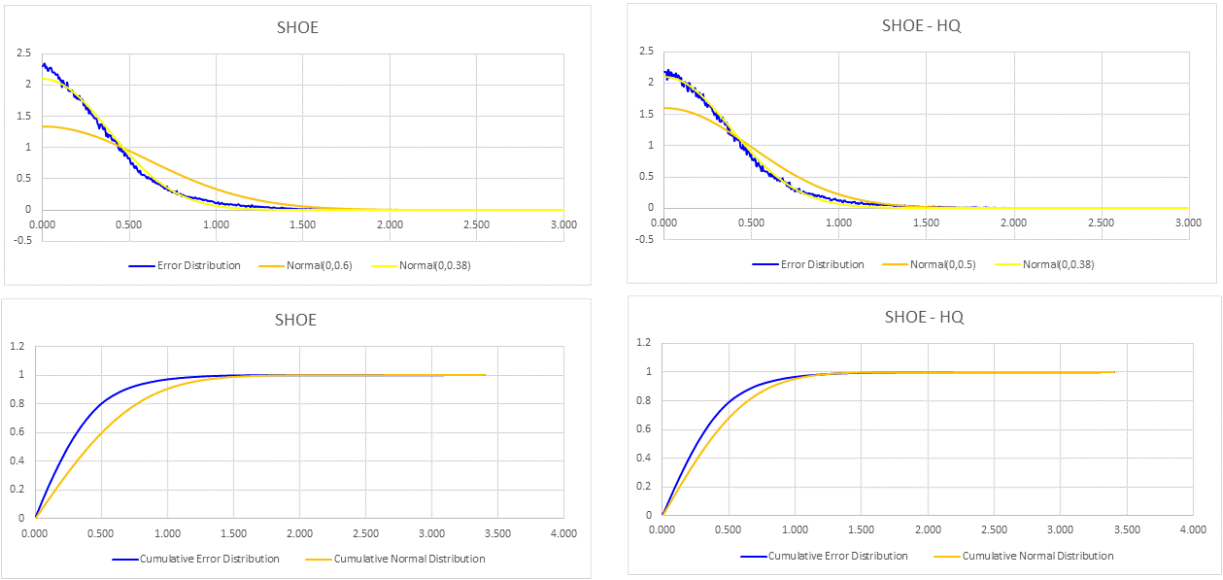


Figure 6-8 Distribution of SHOE Measurement Errors, Galileo

Table 6-2 summarises the station performances:

Station	DARE	ENIS	HERS	INVR	LICC	NTGM	SHOE
Meas Error rms (m)	0.41	0.80	0.35	0.54	0.36	0.42	0.67
Std.Dev. approx. (m)	0.34	0.45	0.32	0.47	0.31	0.55	0.38
Std.Dev. tail (m)	0.50	0.75	0.40	0.70	0.45	0.80	0.60

Table 6-2 Station Performance Characterisation, Galileo Constellation

The obtained results are entirely in line with expectations. The error distributions of all stations follow a very similar pattern though at varying absolute error levels. The absolute error level reflects a range of contributing factors, such as configuration of the station, receiver hardware used, environment. Again, the only station meeting the expected 'overbounding' σ of 0.4m is HERS. The design of a DIM System proposed in the present study stipulates a station performance at least matching that of HERS, the externally steered IGS station. All performances obtained in the current study will need to be extrapolated accordingly.

Figure 6-2 to **Figure 6-8** demonstrate as expected that the distributions of station measurement errors do not follow a normal distribution. In particular, the tail of the distributions is significantly larger than a normal distribution. We must conclude that strict overbounding of the distributions, in the sense that the cumulative distribution (0-x) of the actual errors exceeds that of the overbound for all error values x, will not be possible. This observation is of course in line with all studies in the field.

Table 6-3 characterises the station performance in terms of rms measurement error for L1-L5 dual frequency GPS measurements.

Station	DARE	ENIS	HERS	INVR	LICC	NTGM	SHOE
Meas Error rms (m)	0.80	n/a	0.69	0.89	0.91	0.96	0.71

Table 6-3 Station Performance Characterisation, GPS Constellation

The performance for GPS appears substantially worse than Galileo, with the rms typically doubled. The primary cause lies in the constellation size. With a GPS L5 constellation size of 16, there are numerous instances where stations track three or fewer L1-L5 dual frequency GPS measurements. The synchronisation of the station receiver clock will therefore have been driven by measurements of GPS satellites of older blocks which do not broadcast L5 and hence will not contribute to the L1-L5 dual frequency model. The station behaviour for GPS is neither representative of the DIM user calculations nor of the proposed DIM IMS stations. Furthermore, station clock modelling requires at least four converged residual contributions. The available GPS data simply do not support continuous clock modelling but introduce significant noise into the DIM System models.

Based on these results, the present study does not consider the GPS data sufficiently representative to fit normal distributions around observed GPS measurement error distributions. The availability of GPS Block III satellites broadcasting the L5 signal is expected to increase so that the above challenges will not apply to an operational DIM Service.

6.2 Raw Data - Galileo

Using the measurements characterised in section 6.1, the PoC Testbed modelled the IMS station clocks and Galileo satellite residual errors at the worst user location. **Figure 6-9** shows the resulting number of monitored Galileo satellites for the week from 07 to 13 February 2021. The run underlying **Figure 6-9** used the bias model of satellite error. Algorithms were tuned in line with the performance characteristics of the available measurements, including the cycle slip detection threshold raised to 10 cycles. This tuning does not constitute a recommendation for an operational DIM System.

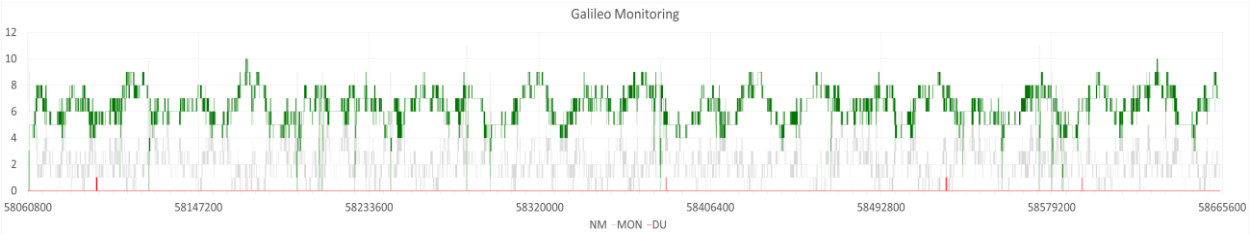


Figure 6-9 Galileo Monitoring

The green line tracks the number of monitored satellites. All instances of total monitoring loss are caused by data gaps within the available EUREF and IGS archives and are not related to algorithm performance issues.

The grey line tracks the number of satellites in view over UK EEZ for which the algorithm was unable to provide integrity modelling so that it issued a Not Monitored (NM) status. The NM count excludes all those satellites which were entirely unobservable across UK EEZ for geometric reasons.

The red line identifies alarms raised by the DIM algorithms. All 4 alarms are false because there are no genuine alarm conditions inside the raw measurements.

6.2.1 Availability

Defining Galileo availability as the share of Galileo satellites with DIM status Monitored out of all the satellites observable from UK EEZ, the PoC Testbed calculated the share of MON satellites of the total. The calculation is based on 22 Galileo satellites, excluding E14 and E18 due to insufficient measurements.

The PoC Testbed achieved availability, i.e., integrity assured monitoring of 78% of observable satellites, with an average of 6.3 monitored satellites. Excluding archive data gaps, the number of monitored, integrity assured Galileo satellites ranged between 4 and 10.

As discussed in section 3.5, there are systematic reasons why not all observable satellites will be monitored. Users in UK EEZ will view rising satellites ahead of any land-based monitoring station and the DIM algorithms models require convergence before their integrity is assured. Section 3.5 placed the resulting inevitable loss of availability at around 10%.

The characteristics of the available measurement data contribute to a significant further reduction of the availability:

- Archive data gaps restart the convergence periods of previously converged satellite models.
- Residual noise, multipath detection, low signal to noise ratio and measurement errors, force the exclusion of measurements from the final satellite model, frequently to the point where insufficient measurements remain to continue modelling.
- Finally, the Galileo constellation size of 22 appears at the lower end of feasibility for integrity monitoring and is expected to grow in time.

6.2.2 False Alarm

Defining Galileo false alarms as incidents where the DIM algorithm considers the alarm threshold breached but the true satellite pseudorange error is below the alarm threshold the PoC Testbed encountered 4 episodes where the DIM algorithms falsely considered a single satellite in alarm, comprising 205 individual epochs. The average duration of 50 seconds of a false alarm episode reflects the high correlation between the measurement errors of consecutive 1Hz measurements.

All 4 episodes occurred on rising satellites which at the time were monitored by just 4 stations with multiple stations experiencing large (in terms of their error distributions) measurement errors.

The false alarm rate of 205 in 604,800 seconds ($=3.4*10^{-4}$), or 205 in 4,888,000 observable satellite models ($=4.2*10^{-5}$) does not fully meet the expectations established in section 3.4.5.6. However, it is clear that a reduction in station measurement error will significantly reduce the probability of simultaneous measurement outliers which underlay all false alarms. The PoC Testbed experimentation validated the numerical assumptions underlying the modelling of section 3.4.5.6: The actual ratio of URE and URA is below 0.5, and evaluation of the HERS data demonstrates that a measurement sample standard deviation of 0.4m or better represents an entirely realistic IMS performance requirement.

6.2.3 Missed Detection

The missed detection probability cannot be established using a week's data set, especially when the available data set does not contain any instances of genuine alarm.

As per section 3.2.5, a missed detection occurs when the true satellite pseudorange error for the worst user exceeds the alarm threshold established by the URA or SISA at 4.42 σ, but no alarm is raised. The integrity algorithms of section 3.4.5 raise an alarm if the modelled adjusted mean (by Student contribution) exceeds the URA or SISA at 4.42 σ. It is therefore a necessary condition for a missed detection that the algorithm modelled adjusted mean is smaller than the true error.

The condition is clearly not sufficient for a missed detection to occur. If both modelled and true errors are below the alarm threshold, the satellite will correctly be set monitored. If both

modelled and true errors are above the alarm threshold the satellite alarm will correctly be raised. Therefore, the probability that the adjusted mean is smaller than the true error represents an upper bound of the missed detection probability. It is also a condition which can be evaluated for each model instance so that the PoC Testbed processed a statistically significant number of samples.

Figure 6-10 plots the distribution of the adjusted mean minus true error. A value below zero indicates that the adjusted mean did not bound the true error and hence the potential of a missed detection exists. Of 383,056 samples (taken at 10s intervals), 1,388 or $3.6*10^{-3}$ failed to bound the true error, for the worst UK EEZ location.

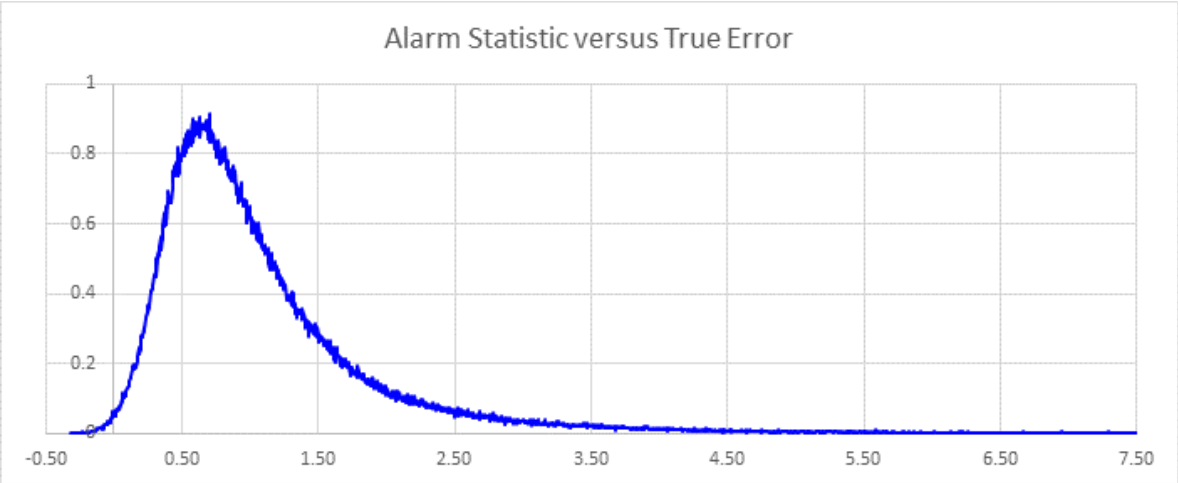


Figure 6-10 Alarm Statistics versus True Error

Section 3.4.5.7 highlights the issue that the performance at sea will be extrapolated from land-based observations. The PoC Testbed analysed the impact on missed detection probability as follows where T is the adjusted mean, E the true pseudorange error for the worst location:

P(T < E for any user in UK EEZ) = $3.6*10^{-3}$

P(T < E for any user in UK mainland) = $3.3*10^{-3}$

P(1.04*T < E for any user in UK EEZ) = $2.9*10^{-3}$

Figure 6-11 presents the accuracy of the mean model as per section 3.4.5.3, that is the modelled estimate of the pseudorange error. The PoC Testbed again finds the expected small deviation from a normal distribution as plotted for reference. We furthermore observe a small bias to the right in the order of 5cm from a fully centred distribution. In section 5 above, we have identified a range of small biases of this order of magnitude that were not fully modelled. Therefore, the observed bias is consistent with the extent of completeness implemented in the PoC Testbed.

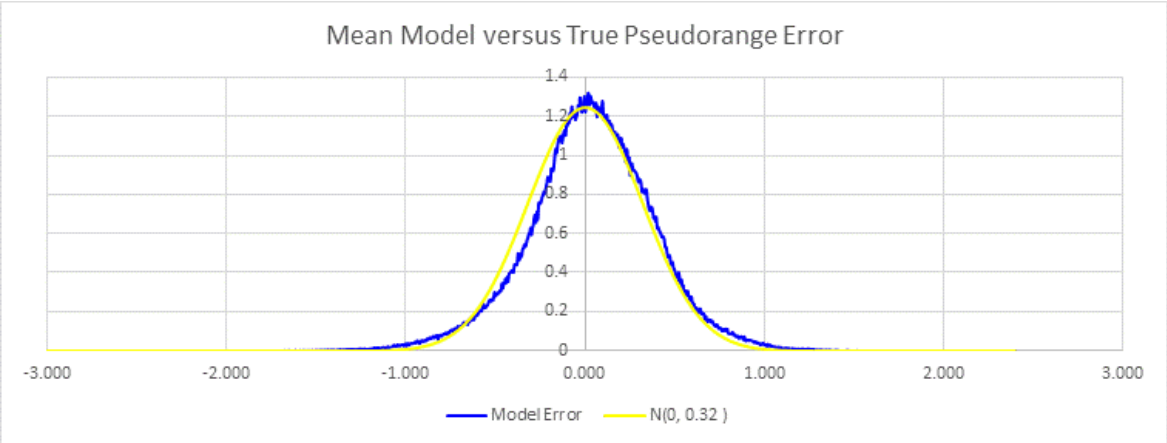


Figure 6-11 Accuracy of the Model

6.3 Raw Data - GPS

Using the measurements characterised in section 6.1, the PoC Testbed modelled the IMS station clocks and GPS satellite residual errors at the worst user location. **Figure 6-12** shows the resulting number of monitored GPS satellites for the week from 07 to 13 February 2021. The run underlying **Figure 6-12** used the bias model of satellite error. Algorithms were tuned in line with the performance characteristics of the available measurements. This tuning does not constitute a recommendation for an operational DIM System.

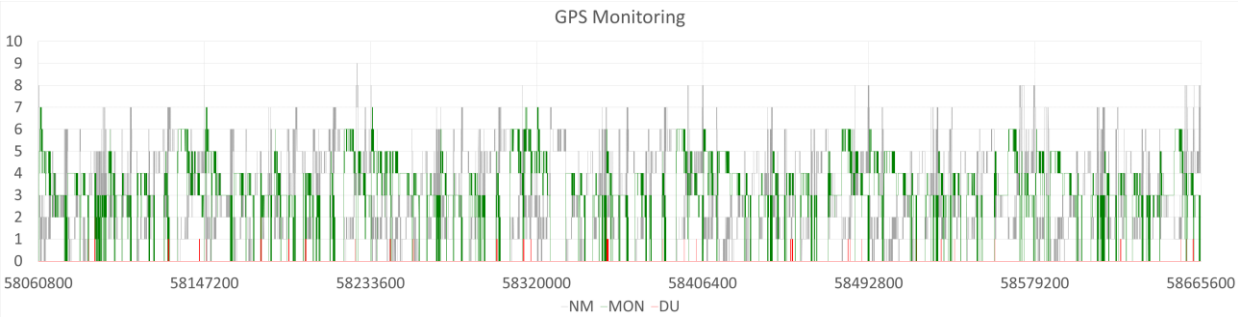


Figure 6-12 GPS Monitoring

The green line tracks the number of monitored satellites, the grey line the number of satellites in view over UK EEZ for which the algorithm was unable to provide integrity modelling so that it issued Not Monitored (NM) status. The NM count excludes all those satellites which were entirely unobservable across UK EEZ for geometric reasons. The red line identifies alarms raised by the DIM algorithms.

We observe that availability, as the share of DIM monitored GPS satellites among observable GPS satellites is around 50% and that on average DIM declared 2.8 GPS satellites monitored. The fundamental cause of the lack of availability lies in the size of the GPS L1-L5 constellation. With only 16 satellites it has not yet reached critical size. Over extended periods, the 7 monitoring stations were only able to track 3 GPS L1-L5 broadcasts. At 3 observations, the algorithm is unable to reach sufficient confidence in its station clock modelling, so that no observations contributed to satellite modelling, leading to frequent monitoring outages. The reduced stability of station clock modelling and the reduced availability of measurements furthermore resulted in a false alarm rate 8 times higher than for Galileo.

We have not attempted to derive representative performance figures for GPS from the available data set because we are confident that with increasing GPS L1-L5 constellation

size the above issues will resolve themselves. We do however note one difference between GPS and Galileo: The lowest and most common Galileo SISA is 3.12m, the lowest, and most common GPS URA is 2.4m when the PoC Testbed identified no superiority of the GPS ephemeris accuracy. It must therefore be expected that the GPS false alarm rate will be more challenging to control than the Galileo false alarm rate.

6.4 Feared Events

The PoC Testbed experimented the injection of feared events such as satellite and station faults into the Galileo constellation only. The GPS raw data quality and quantity was considered so degraded that the injection of equivalent feared event conditions into GPS could not a priori yield the required degree of confidence in the detection performance. At the same time, the PoC Testbed did not identify any reasons why the GPS feared event detection performance should not be equivalent to Galileo's once the GPS L1-L5 constellation size reaches critical mass.

Table 6-4 presents the test cases injected into the Galileo data following the injection approach defined in section 5.4.3 above.

Test Case	Feared Event	Sub-category	S/M	Magnitude	Start Time	Duration (seconds)	PRN	Freq	IMS	Simulation Result
User01	Clock	Bias pre-existing	S	5m	7.2. 02:05	3600	33	All	All	5m offset represented in test statistics, correctly MON throughout because threshold is 13m. When FE ends, range and phase jump observed, triggering DU.
User02				-12m	7.2. 05:40	3600	27	All	All	12m offset represented in test statistics, nominally MON but very close to threshold, so flickering MON/DU. When FE ends, range and phase jump observed, triggering DU.
User03				20m	7.2. 17:20	3600	11	All	All	20m offset represented in test statistics, correctly DU throughout.
User04			M	+/-12m	7.2. 12:59	7200	5, 26	All	All	12m offset represented in test statistics, nominally MON but very close to threshold, so flickering MON/DU for both satellites. When FE ends, range and phase jump observed, triggering DU.
User05				+/-20m	7.2. 14:00	7200	3, 33	All	All	20m offset represented in test statistics, correctly DU throughout, except for NM when impaired monitorability.
User11	Clock	Jump observed	S	0.25m	7.2. 21:03	60	2	All	All	0.25m jump represented in test statistics but below level of detectable jumps. Correctly MON
User12				0.50m	7.2. 21:37	30	2	All	All	0.50 jump represented in residuals and detected as clock jump. Correctly DU.
User13				0.75m	7.2. 22:19	10	2	All	All	0.75 jump represented in residuals and detected as clock jump. Correctly DU.
User14			M	+/-0.25m	7.2. 19:57	30	11, 12	All	All	0.25m jump represented in test statistics but below level of detectable jumps. Correctly MON
User15				+/-0.50m	7.2. 20:19	30	24, 25	All	All	0.50 jump represented in residuals and detected as clock jump. Correctly DU.
User21	Clock	Drift	S	-0.015 m/s	8.2. 04:52	1800	8	All	All	1.5cm/s drift represented in test statistics but below level to trigger re-initialisation. Correctly DU when total reaches 13m.

Test Case	Feared Event	Sub-category	S/M	Magnitude	Start Time	Duration (seconds)	PRN	Freq	IMS	Simulation Result
User22			S	+0.025m/s	8.2. 05:47	1200	8	All	All	2.5cm/s drift represented in test statistics, ENIS line of sight reinitialises. Correctly DU when total reaches 13m.
User23			M	+0.005 / -0.01 m/s	8.2. 00:03 / 8.2 00:19	3600 / 3600	4 / 9	All	All	5mm/s and 1cm/s drifts represented in test statistics. Sat 4 (max error 9m) correctly MON, Sat 9 (max error 18m) DU when error exceeds alarm threshold exceeds 13.5m.
User31	Corrupt	Range jump observed	S	+7m	8.2. 03:01	100	3	All	All	Jump detected, satellite alarm, all lines of sight reinitialised, secondary effect of multipath detection
User32			S	+5m	8.2. 06:31	100	3	E1	All	Jump too small to trigger line of sight re-initialisation, however, delayed secondary effect of multipath detection
User33			S	-5m	8.2. 08:57	100	3	E5	All	Jump too small to trigger line of sight re-initialisation, however, delayed secondary effect of multipath detection
User34			M	+/-7m	8.2. 09:14	100	2, 30	All	All	Jump detected, both satellites alarm, all lines of sight reinitialised, secondary effect of multipath detection
User41	Corrupt	Range drift	S	+0.005m/s	8.2. 22:33	3600	12	All	All	Peaks at 7m error, drift does not trigger line of sight re-initialisation, satellites correctly MON
User42			S	+0.005m/s	9.2. 00:08	3600	11	E1	All	Peaks at 18m, DU correctly raised from perspective of smoothed residuals
User43			S	+0.008m/s	9.2. 01:16	3600	19	E5	All	Drift too small to trigger line of sight re-initialisation, residual error peaks at 18m, satellite correctly DU when error reaches 13m
User44			M	+/-0.005m/s	8.2. 18:02	3600	13, 21	All	All	Peaks at 7m error, drift does not trigger line of sight re-initialisation, satellites correctly MON
User45			M	0.005m/s	8.2. 19:37	3600	1, 31	E1	All	Satellite DU when 11m residual error reached (below threshold, but large sample variance, and residuals behind instantaneous solution)
User46			M	+/-0.1m/s	8.2. 20:45	300	26, 31	E5	All	All lines of sight detect drift and re-initialise, satellite correctly DU.
User51	Cycle slips	Phase jump	S	+0.1m	9.2. 07:24	120	5	All	All	Phase jump carries directly into residual but too small to trigger time series – note that cycle slip detection had to be downgraded.

Test Case	Feared Event	Sub-category	S/M	Magnitude	Start Time	Duration (seconds)	PRN	Freq	IMS	Simulation Result
User52			S	+0.25m	9.2. 08:05	120	9	E1	All	Phase jump carries directly into residual but too small to trigger time series – note that cycle slip detection had to be downgraded.
User53			S	+0.4m	9.2. 08:49	120	5	E5	All	Phase jump carries directly into residual but too small to trigger time series – note that cycle slip detection had to be downgraded. Satellite correctly MON.
User54			M	+/-0.5m	9.2. 05:03	120	4, 36	All	All	Lines of sight reinitialised due to cycle slip detection, satellite correctly DU.
User55			M	+/-0.1m	9.2. 05:47	120	4, 36	E1	All	Phase jump carries directly into residual but too small to trigger time series – note that cycle slip detection had to be downgraded. Satellite correctly MON.
User56			M	+/-0.25m	9.2. 06:11	120	1, 4	E5	All	Phase jump carries directly into residual but too small to trigger time series – note that cycle slip detection had to be downgraded. Satellite correctly MON.
User61	Corrupt	Phase drift observed code-carrier divergence	S	+0.01m/s	10.2. 11:54	5000	1	All	All	For phase drift, the absolute phase value is not significant, only the rate of change. At 1cm/s it remains below detection threshold. Satellite correctly MON.
User62			S	+0.02m/s	10.2. 13:21	3600	5	E1	All	Breaches phase time series after 56s, DU
User63			S	+0.03m/s	10.2. 22:59	3660	9	E5	All	Breaches phase time series after 46s, DU
User64			M	+/-0.02m/s	9.2. 14:10	7200	25, 30	All	All	Rate of drift drives residual error to alarm levels, DU from 14:19 onwards
User65			M	+/-0.03m/s	10.2. 00:16	3600	8, 26	E1	All	Rate of drift drives residual error to alarm levels, DU from 00:31 onwards
User66			M	0.005m/s	9.2. 21:23	5000	13, 15	E5	All	With phase drift, the absolute phase value is not significant, it is the rate of change, at 5mm/s it remains below detection threshold
User71	Ephemeris error	Inclination	S	0.0006%	11.2. 04:40	1200	8	n/a	n/a	7m position error for worst user, satellite correctly remains MON.

Test Case	Feared Event	Sub-category	S/M	Magnitude	Start Time	Duration (seconds)	PRN	Freq	IMS	Simulation Result
User72		Inclination	S	0.001%	11.2. 05:00	1200	8	n/a	n/a	14m position error for worst user, but only 7m detectable from UK land, missed detection.
User73		Inclination	S	0.003%	11.2. 07:10	1200	8	n/a	n/a	34m position error for worst user, 15m detectable from UK land, satellite correctly DU.
User74		Inclination	S	0.004%	11.2. 07:30	1200	8	n/a	n/a	42m position error for worst user, 18m detectable from UK land, satellite correctly DU.
User75		Eccentricity	S	0.1%	11.2. 05:30	1200	26	n/a	n/a	10m position error triggers jump detector
User76		PhiCos, MA	M	100%, 0.0002%	11.2. 06:00	1200	8, 26	n/a	n/a	E08: 7m error, satellite correctly MON E26: 12m, satellite correctly MON.
User77		PhiCos, MA	M	200%, 0.0004%	11.2. 06:20	1200	8, 26	n/a	n/a	E08: 15m error, satellite correctly DU. E26: 14m error, satellite correctly DU.
Syst01	Clock	Jump	S	0.2m	11.2. 12:43	37	All	All	HERS	0.2m jump represented in HERS residuals but does not trigger. Correctly MON.
Syst02			S	0.3m	11.2. 12:49	64	All	All	HERS	0.3m jump represented in HERS residuals but does not trigger. Correctly MON.
Syst03			S	0.4m	11.2. 13:12	1200	All	All	HERS	0.4m jump represented in HERS residuals but does not trigger. Correctly MON.
Syst04			S	0.5m	11.2. 13:32	29	All	All	HERS	0.5m jump represented in HERS residuals, triggers re-initialisation of line of sight. Correctly MON.
Syst05			M	+/- 0.25m	11.2. 14:05	60	All	All	INVR SHOE	0.25m jumps represented in INVR/SHOE residuals, but do not trigger. Correctly MON.
Syst06			M	+/- 0.45m	11.2. 14:16	90	All	All	INVR SHOE	0.45m jump threshold value, SHOE triggers, INVR carries on but satellite statistics remain stable, correctly MON.
Syst11	Cycle slip	Phase jump	S	0.25m	12.2. 05:17	100	5	All	LICC	Phase jump represented in LICC residual, too small to trigger line of sight re-initialisation. Satellite stays correctly MON.
Syst12			S	0.40m	12.2. 05:34	40	5	All	LICC	Phase jump represented in LICC residual, too small to trigger line of sight re-initialisation. Satellite stays correctly MON.
Syst13			S	0.50m	12.2. 05:51	74	5	E1	LICC	LICC line of sight reinitialises. Satellite stays correctly MON.

Test Case	Feared Event	Sub-category	S/M	Magnitude	Start Time	Duration (seconds)	PRN	Freq	IMS	Simulation Result
Syst14			S	-0.35m	12.2. 06:08	20	5	E5	LICC	Phase jump represented in LICC residual, too small to trigger line of sight re-initialisation. Satellite stays correctly MON.
Syst15			M	+/-0.35m	12.2. 06:01	62	5	All	INVR NTGM	All represented in INVR, NTGM residuals, none trigger. Satellites stay correctly MON.
Syst16			M	+/-0.4m	12.2. 06:20	25	5	E1	INVR NTGM	All represented in INVR, NTGM residuals, none trigger. Satellites stay correctly MON.
Syst17			M	+/-0.7m	12.2. 06:39	107	5	E5	INVR NTGM	INVR and NTGM lines of sight re-initialised, satellite remains MON based on 5 unaffected lines of sight.
Syst21	Scintillation	Phase Instability	S	0.3m	12.2. 07:24	500	5	All	HERS	HERS line of sight re-initialised correctly. No impact on satellite status.
Syst22			M	+/- 0.4m	12.2. 07:49	700	5	E5	DARE HERS	DARE, HERS lines of sight re-initialised correctly. No impact on satellite status.
Syst31	False lock	Code offset between freq.	S	-1 m	12.2. 08:33	458	5	E1	SHOE	SHOE residuals marginally impacted, below threshold for triggering time series, satellite remains correctly MON.
Syst32			S	7 m	12.2. 08:59	753	5	E5	SHOE	SHOE residuals represent the bias, SHOE excluded as outlier from satellite model, SHOE line of sight re-initialised, satellite remains correctly MON.
Syst33			M	+/-0.75m	12.2. 09:36	2000	5	E1	DARE INVR	DARE, INVR residuals represent the bias, below threshold for triggering time series, measurements get excluded in final test statistics. Satellite correctly MON.

Table 6-4 Feared Event Experimentation

Based on the experimentation, **Table 6-5** summarises the approximate detection thresholds for feared events. Here, a pre-existing fault condition refers to a fault already present on a rising satellite, an observed condition refers to a fault occurring during the satellite pass.

	Signal Fault	Pre-existing	Observed
Satellite Clock	Jump	12m	0.5m
	Drift	12m	0.5m/s
Satellite Pseudorange	Jump	12m	6m
	Drift	12m	0.1m/s
Satellite Phase	Jump	n/a	0.5m
	Drift	n/a	0.03m/s

Table 6-5 Feared Event Detection Thresholds

Of the 60 test cases, 58 passed without further comment.

Test Case User72 represents a missed detection due to observation geometry. The test case is an example of the geometric condition where the maximum observable residual pseudorange error from UK based stations is below the alarm threshold (at around 7m), but the maximum error to a mariner in UK EEZ is above the alarm threshold (at around 14m). We note that the underlying 3-dimensional ephemeris position error amounted to (Δx, Δy, Δz) = (179m, 97m, -142m). Cases User71 and User 73 demonstrate that for both smaller and larger ephemeris position errors the DIM algorithms deliver the correct result. Our ability to construct case User72 illustrates the general principle of the limitations of extrapolation to the UK EEZ. It is does not however, invalidate the detection capability because it has an almost negligible likelihood of occurrence which will be contained by the missed detection rate.

Test Case User42 passed but highlighted a mechanism by which carrier phase smoothing of pseudoranges may result in medium term model errors. 1000 cycles after the end of the injected condition the smoothed residuals still exhibited a 4m offset compared with an instantaneous solution, or a smoothed solution re-initialised at the end of the fault event. Whilst carrier phase smoothing of pseudoranges is an essential mechanism generally resulting in significant accuracy improvements, some further research may be conducted into the feasibility of a barrier against the behaviour identified by Case User42.

The PoC Testbed did not observe any instances where the detection and elimination of faulty satellites impacted the monitoring status of unaffected satellites. Theoretically, the exclusion of faulty satellites will alter the station clock models so that in threshold cases other satellites could be affected. The number of PoC Testbed experiments was however not statistically significant in this respect.

6.5 Algorithmic Lessons and Tuning

Over the course of the proof-of-concept experimentation, a number of algorithms were tuned and made more robust against certain conditions. The results shown in sections 6.1 to 6.4 were generated from the final PoC algorithms baseline and tuning, having taken into account the lessons of section 6.5.

6.5.1 Station Clock Model

The station clock model must be robust against multiple outliers in order to assure the continuity needed by the final satellite model. The station clock fault detection and isolation mechanism becomes iterative with the decision thresholds tailored to sample size.

Further research should be conducted into the stability of the station clock models across the acquisition and loss of satellite observations from a given station.

6.5.2 Final Satellite Model

The performance of the final satellite model critically depends on the identification and elimination of outliers among the available IMS pseudorange residuals. The PoC Testbed retuned and strengthened multiple qualification criteria for the residuals:

- Exclusion of measurements suspected of medium level multipath. Whilst some multipath, especially at low elevations, must be accepted (to facilitate satellite monitoring at moderate elevations), multipath at low elevation proved the greatest source of false alarms.
- Exclusion of measurements of low SNR, which were also proven to exhibit above average residual errors.
- Detection and elimination of outliers within the set of residuals from all stations, if the reduced sample set affords greater confidence. This again proved beneficial to the false alarm rate but may require further research in the case of genuine geometric differences resulting from projection.
- The PoC Testbed increased the minimum number of converged observations required to monitor a satellite to 4. Whilst the bounding capability and missed detection probability are maintained for sample sets of 2 or 3 residuals the necessary integrity margin (determined by Student factor) results in unacceptable false alarm rates.

6.5.3 4-d Geometry Inversion

The PoC Testbed experimented the alternative final satellite model defined in section 3.4.5.4, consisting of the inversion of the observation geometry in order to estimate the full satellite position error.

Due to geographic constraints, the typical line of sight unit vector from IMS to satellite (0.45, 0.60, 0.81) will vary only 1 to 2% between individual lines of sight. The observation matrix for N lines of sight can therefore be represented as

$$H = \begin{pmatrix} u_{1x} & u_{1y} & u_{1z} & 1 \\ & \dots & & \\ u_{Nx} & u_{Ny} & u_{Nz} & 1 \end{pmatrix} = \begin{pmatrix} 1+\varepsilon_{1x} & 1+\varepsilon_{1y} & 1+\varepsilon_{1z} & 1 \\ & \dots & & \\ 1+\varepsilon_{Nx} & 1+\varepsilon_{Ny} & 1+\varepsilon_{Nz} & 1 \end{pmatrix} \begin{pmatrix} u_x & 0 & 0 & 0 \\ 0 & u_y & 0 & 0 \\ 0 & 0 & u_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

with ε_{ij} of order 10^{-2}.

$$H^T H = \begin{pmatrix} u_x & 0 & 0 & 0 \\ 0 & u_y & 0 & 0 \\ 0 & 0 & u_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} N+\delta_{11} & N+\delta_{12} & N+\delta_{13} & N+\delta_{14} \\ & \dots & & \\ N+\delta_{41} & N+\delta_{42} & N+\delta_{43} & N \end{pmatrix} \begin{pmatrix} u_x & 0 & 0 & 0 \\ 0 & u_y & 0 & 0 \\ 0 & 0 & u_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

with δ_{ij} in the order of 10^{-2}. It follows that the determinant of $H^T H$ is in the order of 10^{-6}.

For a standard least squares estimation, $H^T H$ represents the covariance matrix of the estimated solution parameters. The inversion therefore inflates the standard deviation of the estimated parameters by orders of magnitude, making the solution unviable even for high

quality IMS observations. PoC Testbed simulations generated false alarm and missed detection probabilities orders of magnitude larger than their targets.

While the detection of major geographic trends may be feasible and advantageous in extreme cases such as Test Case User72, the significant overall performance degradation led the PoC Testbed to discontinue experimentation with the geometric inversion algorithm.

6.6 Conclusions

The results of the PoC Testbed replicate other research on the error distributions involved in GNSS measurements. As such, the objectives of the INSPIRe dual frequency multi-constellation service appear broadly achievable. The full benefits of multi-constellation navigation will however only be unlocked when the user receiver hardware overcomes the challenges of local ISB.

The PoC Testbed demonstrates clearly that the GPS L1-L5 constellation has not yet reached critical mass to support an L1-L5 dual frequency service. The GPS constellation will surely reach this point over time.

The PoC Testbed demonstrates the critical importance of measurement quality. The HERS station establishes a floor for the required quality of measurements. The PoC Testbed also provides evidence of the performance degradation impact from lesser stations. We conclude that a DIM Service would be required to maintain their own dedicated stations but note that the PoC Testbed did not attempt to model an alternative using far greater numbers of lesser stations. In order to maintain the required number of residuals contributing to the final satellite model a minimum of 7 stations within the UK will be required.

The PoC Testbed results suggest that the DIM Service's reduction in satellite availability due to incomplete monitoring should be no higher than 15% of all observable satellites.

The PoC Testbed largely achieved its integrity targets, considering that the calculated probability of failure to bound the true error of $3*10^{-3}$ is a significant overestimate of the missed detection probability, which is of course not directly measurable. The PoC Testbed found the missed detection probability across the whole of UK EEZ is around 10% worse than for land-based users. This small degradation appears in line with user expectations at the INSPIRe stakeholder consultation event of 28 February 2023.

The PoC Testbed's false alarm performance clearly does not meet requirements. We feel unable to perform a precise numerical extrapolation of the performance expected from a set of high-quality performing stations, due to the complexity of the models and the fact that error distributions are not normal distributed. We do highlight that the INSPIRe false alarm requirement [C0160] applies to the user's RAIM and is not directly applicable at DIM system level because a DIM system level false alarm on one satellite reduces availability but only in combination with other factors leads to RAIM false alarm.

7 DEVELOPMENT AND IMPLEMENTATION PLAN

This section presents key elements of the remaining development and implementation programme required to create a DFMC Service. It represents the output of WP 7.6 of the INSPIRe programme.

7.1 Technological and Environmental Research

The development of a DIM Service will require completion of the following research topics:

7.1.1 Receiver, Antenna and Clock

A review of receiver hardware, including associated antenna and clock, must be performed to establish if any commercially available models meet the minimum requirements stipulated for the DIM Service in respect of:

- Clock Steering;
- Autonomous detection capability of measurement quality degradation due to amongst others, multipath, cycle slip, or jamming;
- Evil-wave form detection capability;
- Capacity to track at least 12 channels per constellation, and all signals / frequencies which the DIM Service is designed to support.

Whilst suitable receivers likely exist, they may have been developed as bespoke tailorings of more generic commercial receivers in the context of SBAS programmes. The DIM System procurement and development must research the available options and performances and, if necessary, launch bespoke tailoring activities of this long lead item.

7.1.2 Site surveys

The identification of at least 7 IMS sites constitutes a critical long lead item because no acquisition of sites, nor procurement and deployment of site equipment can be started until confidence in the suitability of the sites has been established.

Site location selection will have the objective to achieve maximum geographic spread across the UK land mass. Preselection criteria of the sites will include the availability of, or at least ability to construct, robust network communications facilities. Equally the future operational maintainability, in terms of support infrastructure and in terms of maintaining site security, must be assured for candidate sites.

For all candidate sites, full site surveys must then be undertaken to determine their feasibility in terms of their exposure to multipath and other forms of interference, including intentional or unintentional jamming. Site surveys require extended periods of monitoring due to for example the seasonal variability of vegetation.

7.1.3 Algorithmic Enhancements

The experimentation performed with the PoC Testbed highlighted a number of algorithmic areas which may benefit from additional dedicated research. The topics are:

- A dedicated trade-off between mechanisms to reduce the false alarm probability and improve satellite availability: The two performance objectives are impacted, in opposite ways, by measurement exclusion based on multipath or signal-to-noise

ratio, and by exclusions due to a minimum number of contributing station observations. The optimum criteria and tuning remain to be finalised.

- As highlighted by PoC Testbed Test Case User42 pseudorange smoothing may in certain exceptional circumstances degrade the accuracy of the satellite modelling. Research could either construct a suitable algorithmic barrier or quantify the inherent integrity risk.
- As highlighted by PoC Testbed Test Case User72, some extreme satellite error conditions generate significant differences in satellite residual across UK EEZ. The model based on the mean of observations is not able to recognise such a trend. At the same time, a full 4-dimensional inversion of geometry proved impossible due to the limited footprint of observations. Further research into an algorithmic barrier should be conducted to identify exceptionally strong trends in the residuals' data.
- Further research should be conducted into the stability of the station clock models during the acquisition and loss of satellite lines of sight from a given station.

7.1.4 Proof of Performance

The PoC Testbed provided estimation and extrapolation of final DIM Service performance on the basis of significantly unrepresentative data. Further development of a complete representative performance simulation environment is therefore critically important to underpin the performance models. The key criteria for the collation and generation of test data are:

- Test data shall be representative of the quality, signal-to-noise ratio, clock stability and multipath characteristics established in the receiver research and site surveys;
- The GPS and Galileo constellation sizes reflected in the test data shall be at the level of the fully deployed level, certainly no lower than 24;
- Comprehensive data sets shall include extreme degraded conditions such as significant ionospheric perturbations.

The representative data will form the basis of the proof of DIM Service performance. Three elements shall be determined:

- Proof of integrity: As is well-known and re-confirmed by the PoC Testbed experimentation, error distributions exhibit tails which exceed a normal distribution and thus require overbounding to employ standard Gaussian approaches to missed detection modelling.
- Proof of false alarm rate: This must include a model of how the DIM System level false alarm rate contributes to the false alarm rate of the user RAIM, demonstrating that the DIM System level false alarm rate is compatible with the INSPIRe target [C0160] for a RAIM false alarm rate.
- Feared Events: This shall generate a complete distribution of the detection rate of all feared event types against feared event magnitude.

7.1.5 Dissemination

Dissemination of GNSS integrity warnings via MSI is not a particularly novel concept, and requires little in the way of further research, pending the establishment of institutional agreements with the MSI distributor. This is discussed more in Section 7.2.3.

Dissemination of a live feed of integrity data as an e-Navigation service could be demonstrated in short order using one of a number of Maritime Connectivity Platform (MCP) testbeds, one of which is owned and run by GRAD. A compatible GNSS receiver would be

required to receive and interpret the integrity data. This could either be achieved by employing an existing maritime DGPS receiver, fed by a synthetic RTCM data stream generated by a computer from the received integrity data, or by performing the integrity processing external to the receiver in a software environment. Either way, a demonstration system could be up and running in a short time frame.

Establishing a fully operational end-to-end demonstration of the dissemination of GNSS integrity data as an e-Navigation service will take longer to achieve, and depends on two separate development paths:

1. The development of a compatible user's receiver, able to interpret the integrity data stream and employ it when fixing the vessel's position using GNSS.
2. The deployment of an operational MCP, complete with data communications pathways discussed previously (satellite or mobile telecoms, or VDES).

The first path is discussed more in Section 4.1 on the performance standards of the user's receiver. The second step will require significant development work, since the MCP is in an early stage of development, and in most cases suitable data communications links with vessels (particularly offshore, away from conventional mobile telecommunications coverage) are not yet in place.

7.2 DIM Institutional Framework

A maritime safety of life service must be governed by a comprehensive institutional framework.

7.2.1 Standard

The DIM Service provides integrity assurance, but not augmentation. Therefore, it will not be able to use the existing [MOPS 2006] standard of navigation SBAS broadcasts. A future phase of the INSPIRe programme will instead need to define and adopt an alternative standard. This will put equipment manufacturers in a position to develop user receivers capable of processing the DIM Service messages, and ensure that user receivers interpret the provided integrity assurance information correctly when computing protection levels. The new standard must address the following topics:

- Service definitions and performance targets such as availability, continuity, missed detection, false alarm; definition of DIM Service satellite status, constellations and frequency combinations; where applicable, including all different navigation phases (port, onshore, off-shore);
- User algorithms to calculate the protection level for integrity assured satellites; this includes which multiples of URA / SISA are to be applied, and which integrity degradation is to be applied by off-shore users;
- Hardware standards and performance requirements for receiver equipment, again differentiating between navigation phases;
- Message structure of the DIM Service communications and other external interfaces.

A future phase of the INSPIRe programme will want to identify and engage the competent authority which is in a position to adopt the standard at the earliest.

7.2.2 Qualification and Certification

In addition to the competent authority to adopt the standard governing the DIM Service, the DIM Service will need to be certified, which comprises two main elements:

- The qualification of the DIM System as having been developed to an agreed assurance level commensurate with the user integrity risk;
- The certification of the DIM Service operator concerning their organisational constitution, their processes, their KPIs, and any independent supervision thereof.

The DIM Service certification will therefore need to be performed by a suitable certification authority. A key initial objective ahead of the full DIM System and Service development will be to identify the certification authority and to engage them. The engagement of the prospective certification authority must be completed before any material development activity commences so that all development, design, procurement, implementation, integration and validation will occur under detailed plans and processes which have been validated and approved by the certification authority. Late engagement of certification authorities will result in requests for additional artefacts, retrospective engineering and additional development cost.

The certification authority will accompany the entire development programme, at a level of involvement commensurate with the assurance levels identified for the individual system elements. We expect that the conditions for qualification and certification will include several years of DIM Service operation in a non-safety of life mode, that is, representative service messages marked as ‘do not use for safety of life’ to users.

7.2.3 Dissemination

The dissemination process has been defined as following two distinct paths:

- Dissemination of integrity warnings as MSI
- Dissemination of a live feed of individual satellite integrity status flags as an e-Navigation service.

The promulgation of MSI is already established in the maritime domain, with the sea divided into a number of navigational areas (NAVAREAs), each area has an identified responsible authority, tasked with disseminating MSI within their region of responsibility.

The UK sits within NAVAREA-I, and is also responsible for MSI dissemination in this region. The entirety of the DIM Service area, the UK domestic EEZ, is contained within this area. In the UK, the NAVAREA coordinator is the British Admiralty, with the practical aspects of MSI dissemination conducted by the UK Hydrographic Office (UKHO).

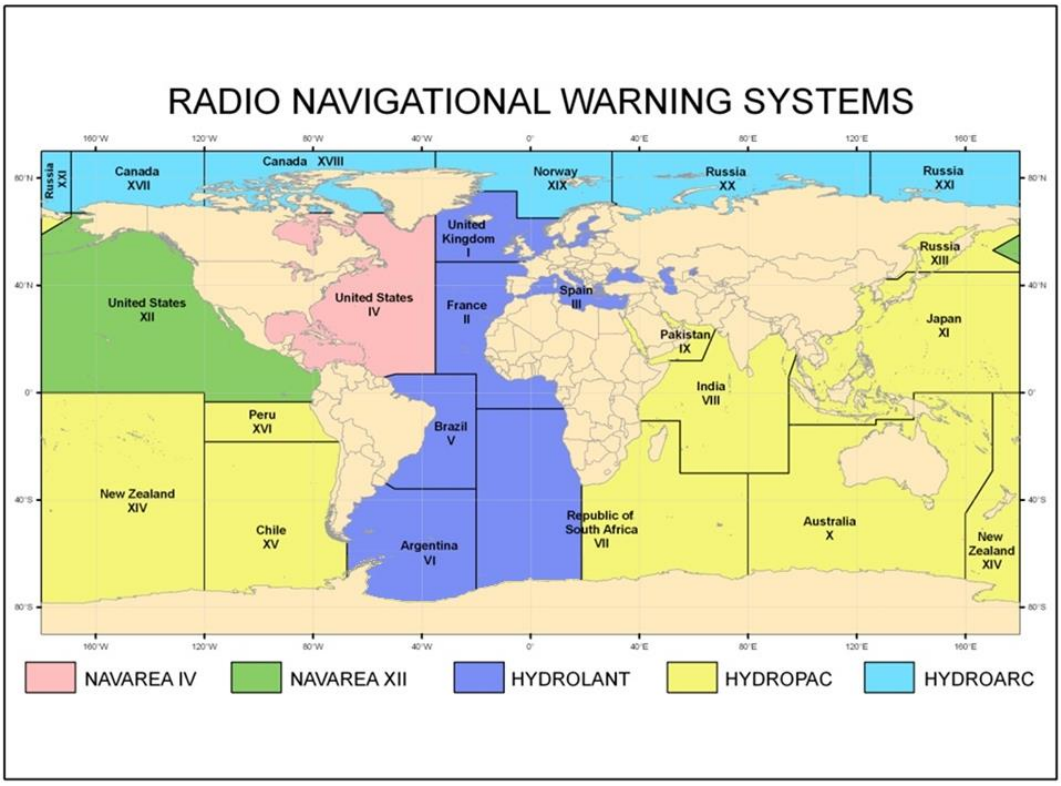


Figure 13 – NAVAREA regions and the authority responsible for dissemination of MSI within those regions

A working agreement between the DIM System operators, and the Admiralty would need to be established. This working agreement would need to determine the roles and responsibilities of both parties, including the content and wording of the MSI; the anticipated frequency of integrity alerts; and the expectations of both parties as to how rapidly the alert can be disseminated to the mariner. It should be noted that the Admiralty are under no obligation to deliver the arbitrary data products of third parties. It would be imperative upon the DIM System operators to seek an agreement that the NAVAREA co-ordinator finds acceptable.

MSI is intended to be human-readable, so the form and content of the integrity messages would need to be agreed, including how an alert is raised, and also cancelled. The form of these messages would also need to be communicated to the mariner, including how they should respond to GNSS integrity warnings delivered by MSI. Some form of education or training may need to precede the broadcast of GNSS integrity by MSI to ensure the information is used correctly, and does not cause confusion on the bridge of the ship.

A communication channel would then be opened, for the DIM System operators to send integrity alerts to the Admiralty, for further promulgation to the maritime users. This communication channel would most likely be an e-mail address to which automated (or semi-automated) messages could be sent.

We recall, however, section 4.2.5.1 above that by its nature dissemination via MSI will be reserved to longer-term alerts impacting all GNSS or at least outages of an entire constellation. The delays inherent in dissemination via MSI, the typical satellite alarm duration and the constraint that no ‘not-monitored’ status can be relayed, cannot support the user’s instantaneous RAIM algorithm.

Dissemination of a live real-time feed of GNSS integrity flags as an e-Navigation service may require far less in terms of institutional agreements. The data dissemination service would

have to be established as an e-Navigation service within the Maritime Connectivity Platform (MCP). This will require both registering the service with the Maritime Identity Registry (MIR) for the purpose of verifying the identity of the service provider, and so issuing the appropriate cryptographic keys (X.509 Certificates, or similar). The service will also have to be listed on the Maritime Service Registry (MSR), so that vessels can search for, locate, and subscribe to the e-Navigation service.

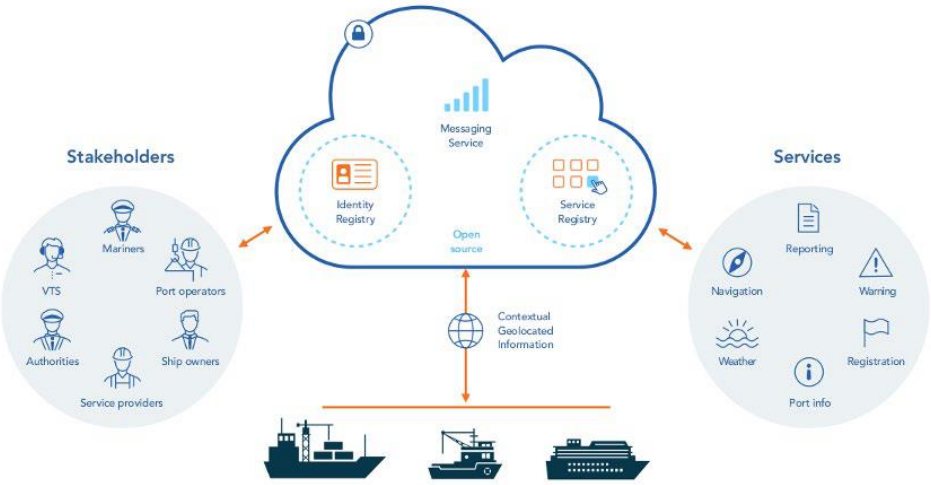


Figure 14 – Basic Architecture of the Maritime Connectivity Platform (MCP)

As discussed before, the conceptual development of the MCP is still relatively immature. It is not yet established whether the mature system will operate as a single instance, centrally administered, or will run in a decentralised fashion with multiple instances administered by local maritime authorities.

The Maritime Connectivity Platform Consortium (MCC) is an international non-profit organisation comprised of multiple organisations that aims to oversee the development of the MCP, its standards and operating procedures. It does not own the MCP, or operate an instance of it, but oversees the establishment of multiple Testbed instances of the MCP worldwide. The General Lighthouse Authorities of the UK operate an MCP Testbed through GRAD. It is through the work of the MCC that MCP conceptual development is progressed, and it is through their work that the necessary institutional framework for the DIM System will become apparent in time.

The existence of multiple MCP testbed instances, and the inherently distributed, open-source and decentralised nature of the development indicates that it is likely that the operational system will run as multiple instances, globally distributed. It is likely that individual maritime authorities will operate their own MCP instances, providing e-Navigation services for their own waters. The DIM System may need to apply for an MIR identity and an MSR listing with multiple maritime authorities, depending on the geographical coverage of the DIM System, and the particular MCP instance that the user employs to access the service.

We should note at this point that the globally distributed nature of the system means that an MCP instance anywhere in the world can be accessed remotely via the internet by any user, and likewise a regional e-Navigation service need not necessarily be hosted by the most geographically adjacent MCP instance. A maritime user in UK waters, obtaining GNSS

integrity data from the UK-based DIM System, may not necessarily do so via a UK-operated instance of the MCP.

7.3 DIM Implementation Plan

The proposed implementation workflow accommodates the long lead items and dependencies of the development.

7.3.1 RAM and Safety

The DIM System development must be based on a safety analysis of the future system and its individual elements. The safety analysis will identify hazards inherent in the system elements and their consequences. This will result in the allocation of development assurance levels and in the establishment of barriers to protect against hazards.

Section 4 on DIM System architecture and design highlighted a number of remaining design trade-offs which had the potential of generating CAPEX and OPEX savings. The safety analysis and allocation will consider the trade-offs and identify the best allocation of assurance levels to different DIM System elements to achieve the overall required level of integrity.

It is therefore essential that the safety analysis and allocation is performed ahead of the development of individual system elements to guarantee that all elements are designed and built to the exact assurance level needed within the overall safety model.

7.3.2 Dissemination

Two parallel implementation paths will have to be followed.

The first is to establish the institutional agreements, message contents, and the mariner's expectations of dissemination of GNSS integrity information by MSI. The timeline for this would be dependent on the Admiralty's receptiveness to disseminating the output from the DIM network to the mariner, and the speed with which a working arrangement can be agreed.

There may also be a required lead-time between the DIM System becoming established and the commencement of MSI integrity warnings. This is not least so that the mariner can be suitably informed and educated about the new messaging protocol, including how to respond to alerts, and the process by which alerts are cancelled. There is uncertainty in the duration of this lead time, depending on the perceived significance of GNSS integrity warnings in bridge operating procedures. A possibly lengthy stakeholder engagement and consultation process may have to be conducted to determine the significance of this change. A worst case scenario would necessitate changes to the International Convention on Standards of Training, Certification and Watch-keeping for Seafarers (STCW), and new training for mariners in how to implement GNSS integrity warnings in their navigation equipment. This could take a decade.

There is also likely going to be significant interest paid to the accuracy of the integrity alerts themselves, in particular the issue of false alerting. The integrity of the MSI process itself is of high importance, and the continued trust the mariner places in the MSI is conditional upon the accuracy of the messages themselves. A high rate of false alarms would be deemed an unacceptable risk to the integrity of the MSI, and the reputation of the Admiralty itself. We

recall, however, section 4.2.5.1 above that by its nature dissemination via MSI will be reserved for longer-term alerts impacting all GNSS or at least outages of an entire constellation. The delays inherent in dissemination via MSI, the typical satellite alarm duration and the constraint that no ‘not-monitored’ status can be relayed, cannot support the user’s instantaneous RAIM algorithm.

The second implementation path: that of dissemination via the MCP as an e-Navigation service, is even further out of the control of the INSPIRe project, or the DIM System operators. A large majority of the MCP infrastructure has yet to be established as an operational system. Indeed, the conceptual notion of the MCP, and the service-based architecture it is built upon, is still in development.

For the e-Navigation service component to become fully operational, the MCP concept would need to be fully mature, and operational instances of the platform established internationally. This will not happen for several years at a minimum.

The data communications infrastructure necessary to disseminate the integrity messages to the ships would need to be established and standardised. VDE-SAT and VDE-TER are both still in the early experimental phase. Radio bandwidth has been allocated, signal waveforms have been proposed, but almost every other aspect of the communications system remains in development. It is unlikely that conventional mobile telecoms will be able to provide sufficient coverage offshore, and LEO communication satellites are currently unable to guarantee the necessary time-to-alert to support the timely dissemination of warnings.

We do not have e-Navigation services yet, and the timeline to their delivery is still uncertain.

7.3.3 Schedule and Work Logic

Figure 4-4 presents a high-level schedule and work flow for the creation of a DIM Service.

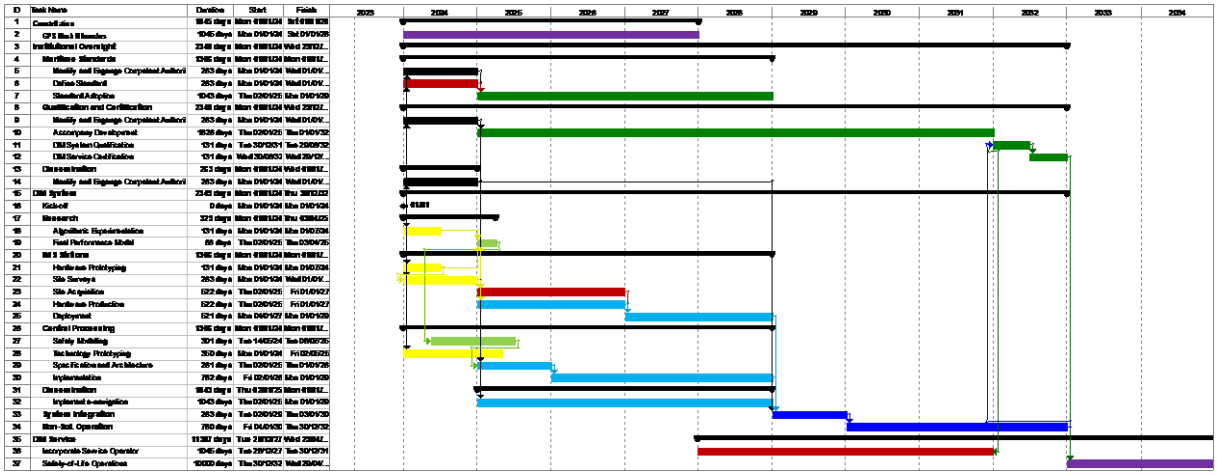


Figure 7-15 DIM Service Schedule

The key dependencies of the workflow are highlighted below:

The GPS constellation is scheduled to reach 24 operational satellites broadcasting L5 in around 2027 according to [GPS Mod 2020].

All competent authorities, relating to standards, communications and to qualification and certification must be identified and engaged at the earliest in order to ensure that the DIM Service development meets all governance requirements.

The finalisation of the achievable algorithmic modelling performance, the selected sites, and the selected technology all critically inform the safety analysis and the finalisation of assurance levels within the DIM System. In turn, the components are mutually inter-dependent in the sense that for example IMS hardware and site selections contribute to the achievable performance. It is therefore a primary objective to resolve these dependencies during the first year of development. This will result in a comprehensive allocation of performance, safety margins and development assurance levels to the system components. On the basis of those allocations, detailed development plans and component designs may then be generated.

Based on comparable developments, the central real-time DIM System is expected to require software, including COTS operating systems and communications, at an elevated assurance level. This will result in restrictions on design and constrain technology choices. The implementation must therefore be preceded by a period of technology prototyping.

The sections on algorithm and PoC experimentation have highlighted the complexities of the environmental physicals, including the well-known deviations of the inherent error distributions from normal distributions. The resulting large tails create significant challenges in the proof of false alarm and missed detection probabilities. The competent authorities of recent SBAS service developments have valued supplementary evidence from extended periods of operations in a non-safety-of-life mode. For maritime, a non-SoL mode will need to be defined in the DIM Service standard. The DIM Service development plan accordingly includes a period of three years between completion of the system integration and the start of safety-of-life operations.

8 COST

The CAPEX and OPEX of a DIM System and Service significantly depend on the degree of synergies with other systems and services. As detailed in section 4.3, synergies will only be realised on the basis of a successful RAMS analysis and completed safety case which fully mitigates the use of commercial elements within the DIM System and the Service. The creation of the RAMS analysis and safety case is beyond the scope of the present study. On the other hand, an assumption that no synergies can be achieved in the final design and safety case would exaggerate the estimated cost. At this stage a bottom-up cost estimation is therefore not deemed appropriate. However, we may establish an indicative order of magnitude of cost by comparing against other concurrent SBAS projects where these have similar safety and assurance objectives and contract value is in the public domain.

[Lockheed 2022] reports “The government of Australia have awarded Lockheed Martin a $1.18 billion contract to establish the Southern Positioning Augmentation Network (SouthPAN) to enhance precision. The system is expected to be fully operational by 2028, and will be provided as a service for 19 years with an option to extend.”[1]

With the geographic size approximately equivalent to the size of the EGNOS Service area, it must be assumed that the number and geographic density of SPAN measurement stations will be of the same order of magnitude, that is around 50. This contrasts with 7 IMS in the DIM System. Hardware and surveying costs will scale with the number of IMS. At the same time, the effort of development and validation of IMS technology will be independent of the number of units ultimately deployed in the field.

SPAN is understood to be a complete SBAS service. Therefore, in addition to satellite integrity monitoring, its central system will perform orbit determination and time synchronisation (ODTS), generate augmentation and monitor the ionosphere. The code basis scales with the number of distinct functions. A DIM algorithm monitoring satellite integrity only will be significantly smaller than one comprising ODTS and ionospheric components. At the same time, the DIM System’s needs for operating system, middleware and real-time monitoring and control elements (RTMC) will be of the same order of magnitude as the equivalent elements of SBAS systems because RTMC is independent of the algorithm kernel.

The DIM Service’s needs for offline performance monitoring, for algorithmic evolution and maintenance all scale with the number of integrity assured service outputs. That is, it will scale with the size of the algorithm kernel.

Qualification and certification processes to be undergone are expected to be similar to those of an SBAS, though the volume of some artefacts scales with the size of source code and deployed hardware.

Overall, the CAPEX plus OPEX to build and operate the DIM Service may therefore be placed in the region of 30% to 40% of a complete SBAS such as SPAN.

[1] Here $ represents AUD at approximate fx rate of 2 AUD per GBP.

9 REQUIREMENT TRACE

This section traces the requirements of [INS Req] which are classified as applicable to the central system to elements of the proposed DIM System algorithm.

Compliance status indicate: C = compliant, C* = compliant requiring interpretation, PC partially compliant, N/A = requirement not considered applicable.

Req.Id	Requirement Text	Status	Compliance comment / justification
A0010	Based on the IMO definition, integrity is described as: The ability to provide users with warnings within a specified time when the system should not be used for navigation due to detected faults or an inability to detect faulted conditions. The purpose of the user- and system-level integrity monitoring systems is to provide integrity to vessels in the UK EEZ, ideally extensible to globally.	C	DIM Service concept detailed in section 3.1.
A0020	The shore-based integrity monitoring system should continuously monitor for integrity events (monitorIntegrity) and send any alerts to the Control Centre (sendIntegrityAlert), via the ODN, for further action. These integrity alerts may also be disseminated to users directly via a relevant transmitter of the system to ensure than the required system level integrity Time-To-Alarm (TTA) is met.	C	DIM Service integrity concept detailed in section 3.1.2, dissemination in section 3.1.3.
A0030	The operational solutions for integrity monitoring should address the needs of current safety related and operationally critical services.	C*	The user needs will be met through the combination of onshore and user components. Refer to section 3.5 for anticipated system performance levels, sections 6.2 and 6.4 for test results.
A0040	The integrity monitoring process shall consider all fault conditions specified in the INSPIRe Threats and Faults List Specification with a reasonable probability of occurence (TBD).	C	Refer to monitored threats detailed in section 3.3, and section 6.4 on the decision threshold for feared events.
A0050	The operational solutions for integrity monitoring shall be expandable to future safey related and operationally critical services, including those associated with eNavigation, STM, and autonomy.	C*	The conceptual architecture of Section 4.1 does not contain any elements which preclude expansion.
B0070	If the system-level integrity monitoring system detects a fault or integrity event it shall issue an alert to GNSS users in the UK EEZ and to the Control Centre.	C	See Sections 4.2.5 and 4.4.3.
B0090	The system-level integrity monitoring system shall detect system-level GNSS faults, performing in accordance with the Non-Functional Performance requirements, that could impact the quality of navigation for users in the UK EEZ towards enabling safe maritime operations.	C	Refer to integrity concept defined in section 3.2 and user feared events section 3.3.1. Test results in section 6.4.
BF0110	The system-level integrity monitoring system shall provide a method of identifying when interference occurs to the system in its local environment.	PC	Station feared event handling in section 3.3.2, to be supplemented by dedicated interference monitoring in future enhancement.
C0050	Ocean Phase Time-to-Alarm as soon as practicable by Maritime Safety Information (MSI) systems	C*	See Section 4.2.5 and 4.4.3. Note that MSI is only intended to communicate long term whole constellation issues.
C0100	Coastal Phase "An integrity warning of system malfunction, non-availability or discontinuity" with TTA of 10 seconds	C	See Sections 4.2.5.2 and 4.4.3.

Req.Id	Requirement Text	Status	Compliance comment / justification
C0150	HEA and Restricted Water Phase "An integrity warning of system malfunction, non-availability or discontinuity" within 10 seconds	C	See Sections 4.2.5.2 and 4.4.3.
C0160	Risk of false alarm of 1e-5 per epoch	C*	The DIM System is part of a system of systems. The user needs are met through the combination of local and central systems. The numerical value of 1e-5 per (150s) epoch is mandated for the user MRAIM solution. Individual system level satellite false alarms do not trigger directly trigger MRAIM false alarm. The level of false alarms directly from the DIM Service is therefore not given by the requirement set. See Galileo actuals in section 6.2.2.
CF0190	Ocean Phase: A.915 Specifies TTA of 10s	NA	Future enhancement, IMS and central processing are compliant but depend on dissemination schedule, see Sections 4.2.5 and 4.4.3.
CF0330	Port Phase: A.915 Specifies TTA 10s	NA	Future enhancement, IMS and central processing are compliant but depend on dissemination schedule, see Sections 4.2.5 and 4.4.3.
CF0370	Autonomous Ocean Phase: GSA survey specifies TTA <8s	NA	Future enhancement, IMS and central processing are compliant but depend on dissemination schedule, see Sections 4.2.5 and 4.4.3.
CF0420	Autonomous Coastal Phase: GSA survey specifies TTA <6s	NA	Future enhancement, IMS and central processing are compliant but depend on dissemination schedule, see Sections 4.2.5 and 4.4.3.
D0060	The shore-based integrity monitoring system shall have, and be compatible with, degrees of redundancy including multiple receivers.	C	DIM System Architecture has built in redundancy to meet performance targets during temporary loss of individual IMS or central facilities. See sections 3.4.5 and 4.2. The level of built-in station redundancy drives p_{fa} and p_{md} rates of Galileo actuals in section 6.2.2.
D0100	Proposed integrity monitoring solutions shall be verifiable and validatable subject to real-world considerations including the possibilty of simultaneous faults, for RAIM algorithms providing a protection level this should be through mathematically rigorous approaches (proof of safety, statistical confidence).	C	Live captures and injection tools available. Sub-requirement relating to RAIM is n/a at system level. See Sections 6.2 and 6.4.
D0120	Shore-based system integrity monitoring solutions shall work in the UK EEZ, and may work globally irrespective of jurisdiction/geography.	PC	Refer to sections 3.2 and 4. Solutions have been chosen based on local geography and environmental conditions, which will require retuning and local adaptation.
E0010	The shore-based integrity monitoring system should be compatible with the architecture specified in MarRINav D5 S3.2.4 - Conceptual Operating Architecture: Integrity Monitoring Sites, pp94-96.	C*	Architecture and design requirements imposed on IMS in sections 4.1, 4.2 and 4.4 are compatible.

Req.Id	Requirement Text	Status	Compliance comment / justification
E0020	Integrity solutions shall be tested, using simulated or real data, to demonstrate the performance of the integrity solution for all threats and faults in accordance with the test scenarios defined in the INSPIRe Test Scenarios Specification.	C	See section 6, in particular subsections 6.2 and 6.4.
E0090	Digital interfaces should be consistent with the NMEA-0183 interface standard	N/A	The requirement is considered applicable to communication inside the vessel only. See sections 4.2.4.1 and 7.2.1.

Table 9-1 Requirements Trace

10 REFERENCES

[Bevis 1994] Bevis, M. et al., *GPS Meteorology: Mapping Zenith Delay onto Precipitable Water*, American Meteorological Society, vol. 33, pp 379-386, 1994

[DFMC SARPS] Navigation Systems Panel (NSP) DFMC SBAS SARPs Sub Group (DS2), *Working Paper: DFMC SBAS SARPs – Part B Version 2.0*, DS2/WP/3 v2.0, 15/11/2018

[EGNOS SDD 2016] EGNOS Safety of Life (SoL) Service Definition Document, rev. 3.1, 26/09/2016

[Galileo ICD] *European GNSS (Galileo) Open Service Signal-in-Space Interface Control Document*, OS SIS ICD, Issue 2.0, January 2021

[GENS 2022] Hudson, D., Glover, J.S., UK GENS Programme Final Presentation, 08/06/2022

[Gioia 2015] Gioia, C, Borio, D, *GGTO: Stability and Impact on Multi-constellation Positioning*, Proceedings of the 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2015), Tampa, Florida, September 2015, pp. 245-249.

[GPS ICD] *NAVSTAR GPS Space Segment/Navigation User Interfaces*, IS-GPS-200, Issue M, 21 May 2021

[GPS Mod 2020] New Civil Signals, https://www.gps.gov/systems/gps/modernization/civilsignals/#L5, 10/08/2020

[Heng 2011] Heng, L, Xingxin Gao, G, Walter, T, Enge, P, *Statistical Characterization of GPS Signal-In-Space Errors*, Proceedings of the 2011 international technical meeting of the Institute of Navigation, January 2011, pp. 312-319

[Hernandez 2009] C. Hernández, C. Catalán & M. A. Martínez, *Galileo Integrity Concept and its Applications to the Maritime Sector*, TransNav, Vol 3 Number 3, September 2009, pp. 287-291

[INS Req] Requirement Specification, S-062-001-001, V1.0, 01/11/2022

[INS Thr] Threats and Faults List Specification, S-062-001-002, 01/11/2022

[Lockheed 2022] Lockheed Martin Awarded SouthPAN Contract, https://www.lockheedmartin.com/en-us/news/features/2022/lockheed-martin-awarded-southpan-contract.html, last edited 16 September 2022

[Mach 2006] Johannes Mach, Ingrid Deuster, Robert Wolf, Wolfgang Werner, *Making GNSS Integrity Simple and/ Efficient – A New Concept Based on Signal-in-Space Error Bounds*, Proceedings of ION GNSS 2006, Fort Worth, TX, 26-29 September 2006, pp. 2666-2677

[Martelluci 2009] Martellucci, A and R. Prieto Cerdeira, R., *Review of tropospheric, ionospheric and multipath data and models for Global Navigation Satellite Systems*, 3rd European Conference on Antennas and Propagation (EuCAP), Berlin (Germany), 2009, 3697-3702

[MOPS 2006] Minimum Operational Performance Standards for Global Positioning System / Wide Area Augmentation System Airborne Equipment, RTCA DO-229D, 13/12/2006

[NAV CS] *Detector based in carrier phase data: The geometry-free combination*, https://gssc.esa.int/navipedia/index.php/Detector_based_in_carrier_phase_data:_The_geometry-free_combination, last edited on 08 July 2014

[NAV SBAS] , *The SBAS Integrity Concept Standardised by ICAO: Application to EGNOS,* The SBAS Integrity Concept Standardised by ICAO: Application to EGNOS https://gssc.esa.int/navipedia/index.php/The_SBAS_Integrity_Concept_Standardised_by_ICAO:_Application_to_EGNOS, last edited 3 August 2016

[NAV MP] *Multipath*, https://gssc.esa.int/navipedia/index.php/Multipath#:~:text=Theinterference%20by%20multipath%20is,the%20satellite%20with%20low%20elevation, last edited on 23 February 2012

[NAV SMOOTH] *Code-Carrier Divergence Effect*, https://gssc.esa.int/navipedia/index.php/Code-Carrier_Divergence_Effect, last edited on 23 February 2012

[NAV TRF] *Reference Frames in GNSS - Navipedia (esa.int)*, https://gssc.esa.int/navipedia/index.php/Reference_Frames_in_GNSS#Current_Galileo_Terrestrial_Reference_Frame, last edited on 23 February 2021, at 12:30.

[Nguyen 2022] C T Nguyen, S T Oluwadare, N T Le, M Alizadeh, J Wickert, H Schuh, *Spatial and Temporal Distributions of Ionospheric Irregularities Derived from Regional and Global ROTI Maps,* Remote Sens. 2022, 14(1), 10

[OS SDD 2021] *Galileo – Open Service – Service Definition Document*, Issue 1.2, November 2021

[Paziewski 2015] Jacek Paziewski, J and Wielgosz, P, *Accounting for Galileo–GPS inter-system biases in precise satellite positioning*, J Geod (2015) 89:81–93

[SPS 2020] *Global Positioning System Standard Positioning Service Performance Standard*, 5th edition, 2020

[Thevenon 2014] Thevenon, P., Tessier, Q., Maillard, D., Cabantous, M., Amarillo-Fernández, F. et al.. *Detection Performances of Evil Waveform Monitors for the GPS L5 Signal*. ION GNSS+ 2014, 27th International Technical Meeting of The Satellite Division of the Institute of Navigation, Institute of navigation, Sep 2014, Tampa, Florida, United States.

[Walter 2017] Walter, T. and Blanch, J, *Improved User Position Monitor for WAAS*, Navigation, Vol. 64, No. 1, Spring 2017, pp. 165-175

[Walter 2018] Walter, T., Shallberg, K., Altshuler, E., Wanner, W., Harris, C., Stimmler, R., *WAAS at 15*, Volume 65, issue 4, Winter 2018, pp. 581-600