



## INSPIRe Final Report D0.5 – WP0 Report

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## 1 EXECUTIVE SUMMARY

According to the Centre for Economics and Business Research, in 2019, the maritime sector contributed an estimated £55.5 billion in direct turnover to the UK economy [34], across activities including shipping, ports, renewable energy, aquaculture, and leisure.

Maritime operations are heavily reliant on trustworthy navigation information from onboard systems in order for the mariner to conduct safe and compliant operations. The need for trustworthy navigation information is becoming ever more vital as maritime traffic grows, the sea space becomes ever more complex, and as vessels become more autonomous.

To guarantee the continued safety and performance of maritime operations, and to provide assurance as future operations which rely on navigation systems are developed, it is essential to improve the monitoring and integrity of the positioning information.

The INSPIRe (Integrated Navigation System-of-Systems Position, Navigation, and Timing (PNT) Integrity for Resilience) project, funded by ESA under NAVISP Element III, has investigated and developed integrity monitoring approaches which provide means for users to monitor the integrity of their GNSS derived positioning information.

The project assembled industry leading R&D and engineering expertise from across the maritime and PNT sectors to develop eight next-generation integrity solutions aligned with the needs of the maritime sector. Each solution represents advancements in integrity monitoring capability. The solutions complement each other and are designed to be integrated as a system-of-systems integrity architecture. They aim to alert the user when there is a problem with the navigation system to ensure trust, and form part of a wider solution that is required to address the need for an increasingly resilient PNT capability.

To ensure a consistent development approach to the integrity solutions, the project developed a set of project requirements. These requirements represent both the current needs of mariners and future developing needs which will become increasingly relevant as future use cases are adopted. The requirements were developed considering key maritime use cases, and the results of previous studies. They were validated with maritime and PNT stakeholder communities to ensure that they provided a representative requirement set. Each integrity solution developed by the project has been validated against these project requirements throughout the development process.

At the user-level (consisting of ship-borne algorithms within users' receivers) four approaches have been developed with each advancing integrity monitoring capability at the receiver:

- MG-RAIM provides a simple to implement algorithmic approach which requires minimal changes to receivers, providing improved user-level integrity aligned with existing maritime navigation performance requirements.
- M-RAIM adapts the aviation-derived ARAIM approach to the horizontal domain to increase its suitability for maritime users, considering future receiver equipment and looking to future navigation performance requirements to provide integrity monitoring which can be configured to the mariner's environment.
- VAIM integrates the MG-RAIM and M-RAIM approaches with dead reckoning navigation to provide an additional layer of integrity monitoring, further improving the integrity monitoring capabilities.
- Crowd-sourcing methods are considered to demonstrate how signals of opportunity such as ranging sensors and sharing of PNT information between vessels can further benefit integrity monitoring.

These user-level solutions are shown to provide algorithms with increasing integrity monitoring capability. They aim to support the technical development of standards which can in turn support a widespread adoption of integrity in maritime nationally and internationally, both for current use cases and for the needs of the future mariner. Specifically, the results of

this project provide validated algorithms, identify the development activities required to mature the solutions to the necessary maturity for implementation in standards, and demonstrate the potential performance of such solutions.

These solutions provide algorithms that can be implemented immediately in receivers where mission criticality is low. For example, the leisure sector provides a sector ripe for implementation where innovations can be quickly implemented. Such early deployment will support the ongoing education of the benefits of integrity monitoring and provide example implementations that can be used to further validate the integrity monitoring approaches. This will then enable improved assurance of GNSS information for specialised use cases to allow GNSS to be utilised in scenarios with high mission criticality.

At the system-level, two integrity monitoring concepts have been developed to utilise shore-based monitoring infrastructure:

- The DFMC Integrity Monitor provides integrity monitoring of GNSS constellations using a network of receiver stations to identify integrity status and disseminate integrity flags to users within the UK EEZ.
- The EGNOS Monitor provides a means to assure the use of the European SBAS's Safety of Life service for users within the UK EEZ.

These system-level solutions provide candidate systems which can be implemented to support a national resilient PNT capability for the UK EEZ. The results of this project demonstrate the potential performance of the systems, but acknowledge that ongoing development, liability provision and safety assurance will be required to implement the systems to the required level of guarantee.

Two additional supporting solutions were developed:

- RAIM Performance Prediction Tool was developed as a supporting tool to enable users to predict the integrity of their GNSS over a voyage.
- Novel Error Characterisation techniques were investigated to demonstrate means of better characterising errors in integrity monitoring algorithms to improve performance.

The RAIM Performance Prediction tool also provides potential for immediate benefit. The tool provides a concept which can be implemented in voyage planning software to enable users to plan their mission with knowledge of the predicted integrity of their GNSS solution over their voyage.

The functionality and performance currently demonstrated by INSPIRe's integrity architecture shows the potential to provide net socio-economic benefits of up to £2.2bn over a 20-year period when applied to key current and developing use cases in the maritime sector. This represents a benefit-cost ratio of 7:1 when scaled nationally and when considering the costs associated with implementing the system-level solutions. There is significant potential to further expand this benefit providing that integrity can be provided to greater levels of accuracy performance.

To progress towards a widespread implementation of the integrity architecture both nationally and internationally, three key future workstreams are identified:

- The maritime RF environment needs to be characterised to understand the effects of local errors for user receivers. This will enable user-level solutions to be configured, further developed, and validated in a representative maritime environment to establish integrity risk requirements, and hence representative assurance of the user-level solutions. This activity will require long-term data collection on a variety of vessels in various environments.
- International standards need to be drafted and developed to integrate integrity into maritime standards. This will require education of the need for integrity to mariners, extensive use case analysis with maritime users to identify the necessary

performance requirements, consideration of the wider PNT architecture, and adoption within the IEC and IMO.

- Continued technical development of both the user-level and system-level solutions is required, both to mature the solutions and to improve their integrity monitoring capabilities to expand the applicable use cases. Several key opportunities for development are identified within this project; for example, through ongoing validation using extended data, by utilising crowdsourcing concepts and by integrating adaptive error modelling within the algorithms.

Overall, INSPIRe has investigated and validated a number of technical solutions for monitoring the integrity of a mariner's GNSS solution. These solutions can be integrated to provide an integrity monitoring architecture, and represent part of the ongoing technical development required to achieve a resilient PNT architecture that is fit for future requirements.

Immediate benefits can be realised for users, especially when considering the potential of the non-regulated maritime sector to demonstrate and mature use cases and the technical solutions themselves.

Over the longer-term, integrity needs to be adopted through international standards to ensure a widespread improvement in safety and enable mission critical use cases which depend on navigation systems. The results of INSPIRe provide an initial framework for this, however continued and coordinated development of technical solutions, standards and system-level components will be required in order to achieve the required level of capability.

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### 3 GLOSSARY AND REFERENCES

#### 3.1 Change Record

Issue / Rev	Date	Change Record	Authors
v1.0		First Draft	Taylor Airey

#### 3.2 Glossary

Acronym	Definition
AAIM	Aircraft Autonomous Integrity Monitoring
AIS	Automatic Identification System
ARAIM	Advanced Receiver Autonomous Integrity Monitoring
BCR	Benefit Cost Ratio
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CCS	Carbon Capture and Storage
CNI	Critical National Infrastructure
ConOps	Concept of Operations Concept of Operations
CORS	Cross-origin Resource Sharing
DFMC	Dual-Frequency Multi-Constellation
DIM	DMFC Integrity Monitoring
DOP	Dilution of Precision
DR	Dead Reckoning
EEZ	Exclusive Economic Zone
EGNOS	European Geostationary Navigation Overlay Service
eLORAN	Enhanced Long Range Navigation
EMSA	European Maritime Safety Agency
ESA	European Space Agency
EU	European Union
FAA	Federal Aviation Authority
FTE	Full Time Equivalent
GEO	Geostationary Orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GVA	Gross Value Added
H-ARAIM	Horizontal ARAIM
HMI	Hazardously Misleading Information
HPL	Horizontal Protection Level
IMO	International Maritime Organisation
INSPIRe	Integrated Navigation System-of-Systems PNT Integrity for Resilience
LEO-PNT	Low-earth orbit PNT
LiDAR	Light Detection and Ranging
LOS	Line Of Sight
LPV	Localizer Performance with Vertical Guidance
M(G)RAIM	Maritime General RAIM
MarRINav	Maritime Resilience and Integrity of Navigation
MASS	Marine Autonomous Surface Ships
MCP	Maritime Connectivity Platform

MCP	Marine Connectivity Platform
MIR	Maritime Identity Registry
MPAs	Marine Protected Areas
MRAIM	Maritime RAIM
MSI	Maritime Safety Information
MSR	Maritime Service Registry
NAGUs	Notice Advisory to Galileo Users
NANUs	Notice Advisory to Navstar Users
NLOS	Non-Line of Sight
NPA	Non Precision Approach
NPV	Net Present Value
OPEX	Operating Expenses
PL	Protection Level
PNT	Position, Navigation, and Timing
PoC	Proof of Concept
PVT	Position, Velocity and Time
QoS	Quality of Service
RAIM	Receiver Autonomous Integrity Monitoring
RINEX	Receiver Independent Exchange
SAR	Search and Rescue
SBAS	Space-based augmentation system
SOLAS	Safety of Life at Sea
VAIM	Vessel autonomous integrity monitoring
VDES R-Mode	VHF data exchange system R-Mode
VHF	Very High Frequency
WAAS	Wide Area Augmentation System

### 3.3 Project Reports

Ref	Description	Issue/Rev
D1.1	Systems Engineering Report	3.1
D2.1	Algorithm documentation (GPS M(G)RAIM) Report	1.3
D3.1	Algorithm development (DFMC M(G)RAIM) report	1.2
D4.1	Algorithm development (DFMC & DR VAIM) report	1.1
D5.1	EGNOS Prototype Monitoring Station report	1.1
D6.1	RAIM prototype report	1
D7.1	DFMC integrity monitoring report	1.1
D8.1	Crowd-sourced inputs into DFMC integrity report	2
D9.1	Infrastructure & full CBA Review (ICR)	Final
D10.1	Outline integrity system design, development & exploitation plan	1.2
D11.1	Stakeholder engagement report	2

### 3.4 Project Reference Documents

Ref	Description	Issue/Rev
Data1.2	Test and Validation data for D1.1	1
Alg2.1	Algorithm documentation (GPS M(G)RAIM)	1
Data2.1	Test and validation data for Alg2.1 (GPS M(G)RAIM)	1

Spec2.1	Functional and software design and test specifications (GPS M(G)RAIM)	1
Spec3.1	Functional and software design and test specifications (DFMC M(G)RAIM)	1
Data3.1	Test and validation data for Alg3.1 (GPS M(G)RAIM)	1
Alg3.1	Algorithm documentation (GPS M(G)RAIM)	1
Spec4.1	Functional and software design and test specifications (DFMC & DR VAIM)	1
Data4.1	Test and validation data for Alg4.1 (DFMC & DR VAIM)	1
Alg4.1	Algorithm documentation (DFMC & DR VAIM)	1
Spec8.1	Functional and software design and test specifications (crowd-sourced inputs into DFMC integrity)	1
X-062-001-002	Requirements Checklist	DRAFT
X-062-001-008	Safety and Security Risk Analysis	0.1
S-062-001-001	INSPIRe Requirements Specification	1.3
S-062-001-002	Threats and Faults List Specification	1.1
S-062-001-003	INSPIRe Test Scenario Specification	1
X-062-001-006	Mission Use Cases List	1

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## 4 INTRODUCTION

### 4.1 Project Introduction

INSPIRe has evaluated, developed, implemented and validated integrity concepts which monitor and enhance integrity for GNSS-based PNT, to demonstrate integrity solutions which are suitable for the maritime sector. The integrity concepts are developed to monitor threats and faults in the GNSS solution and alert the user when the positioning solution cannot be trusted.

INSPIRe builds on previous work completed by MarRINav in 2020. The MarRINav project addressed the needs for Critical National Infrastructure (CNI) to provide resilience and integrity for PNT in the UK maritime sector [1]. The INSPIRe project focuses on developing the integrity aspects of the MarRINav project, such as integrity monitoring and driving integrity solutions for currently available sources of PNT data, which is a central aspect of developing more resilient PNT with the aim of providing a cost-effective user-level integrity solution for current GNSS users in the UK maritime sector based on requirements developed through the project.

This document is the Final Report of the INSPIRe (Integrated Navigation System-of-Systems PNT Integrity for Resilience) project. This report summarises the content of all technical reports completed within INSPIRe.

The INSPIRe project began by defining its view of what was meant by integrity:

*“Integrity is about providing a level of confidence to the user that the PNT data received is sufficiently reliable for the manoeuvres in progress at that time and warning the user if it is not. Navigation system integrity is comprised of two components. System level integrity and user-level integrity. System level integrity ensures that the raw signals transmitted by the satellites are not compromised. User-level integrity ensures that good satellite signals have not been degraded at the point of use by local factors. PNT integrity is critical to support the growing use of such data in the maritime sector, heightened when the room to manoeuvre is reduced due to increase maritime infrastructure, such as offshore renewable energy production and with the potential future increase of autonomous vessels, where the human factor is removed.”*

In simple terms, integrity means providing a level of confidence in the PNT solution as well as ensuring that the data displayed to the user is sufficiently reliable for the manoeuvres in progress at the time, and alerting the user if it is not.

The main objectives of INSPIRe are to:

- Investigate, develop and bench test techniques and algorithms for autonomous user-level integrity monitoring
- Build a prototype for EGNOS performance monitoring
- Develop exploration plans for an e-Navigation service to provide supplementary integrity data to vessels

### 4.2 Integrity concepts developed by INSPIRe

INSPIRe has developed integrity monitoring concepts and algorithms both at the user-level and system-level. These are:

#### 4.2.1 User Level Integrity Algorithms

The user level integrity algorithms monitor GNSS faults at the receiver, both considering faults in the local environment and system-level faults where these can be detected. The user-level integrity algorithms developed in INSPIRe are:

- Maritime General RAIM (MG-RAIM) – detailed in section 11

- Maritime RAIM (M-RAIM) – detailed in section 11
- Vessel autonomous integrity monitoring (VAIM) – detailed in section 11

The integrity algorithms have been evaluated in various configurations; using single frequency GPS L1 and DFMC GNSS, and with and without augmentation using SBAS.

INSPIRe also developed a proof-of-concept of a novel method for improving integrity performance.

- Peer-to-peer data sharing - uses ship-to-ship communications and ranging sensors to check the coherence of positioning information between vessels and improve integrity performance

#### **4.2.2 System Level Integrity Concepts**

The system level integrity concepts enable constellation faults and atmospheric effects to be monitored using shore-based monitoring networks to support the user in identifying faults which they may not be able to detect using a single receiver. INSPIRe has developed:

- UK dual frequency, multi-constellation (DFMC) Integrity Monitor (DIM) – detailed in section 11
- UK EGNOS Monitor – detailed in section 11
- Opportunistic sources of data for DFMC integrity monitoring are explored - detailed in section 11

#### **4.2.3 Supporting Tools**

The following concept has been developed as a supporting tool:

- RAIM Performance Prediction Tool - detailed in section 11

### **4.3 INSPIRe Requirements Set**

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INSPIRe has developed a set of requirements to define operational, functional, non-functional and performance requirements for a GNSS integrity architecture for maritime at the user-level.

Details of the requirements are in Section 10.

The requirements are applied to and validated for each of the integrity concepts to demonstrate that the integrity concepts meet the needs of the maritime sector and can be integrated as an architecture.

- The operational requirements provide a high-level Concept of Operations (ConOps) for a GNSS integrity architecture.
- The functional requirements define the practical objectives for the integrity architecture, and the non-functional requirements cover compatibility and integration with other systems.
- The performance requirements set out performance bands per voyage phase to identify the required level of navigational performance. These performance bands are based on extant maritime performance requirements, considering the world wide radio navigation system (WWRNS) performance requirements stated in IMO resolution A.1046(27) with modifications to provide requirements which can be implemented at the user-level.
- A set of future functional requirements are set out considering provision of quantised numerical integrity information, identifying cause of integrity failure and interference detection.

The results from INSPIRe have been used to identify future development pathways for integrating the project's results and novel integrity concepts into a system-of-systems

integrity architecture, and to identify opportunities to exploit this in and beyond the maritime sector.

**4.4 Summary**

INSPIRe has successfully completed the following work packages:

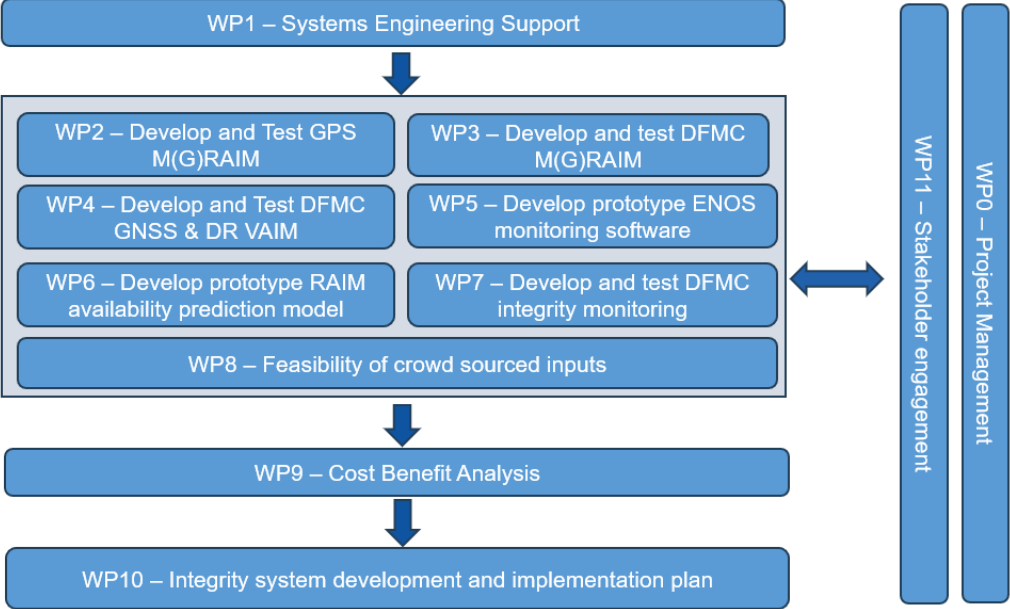


Figure 1 - INSPIRe Work Package Structure

This report shows the advancements and contributions INSPIRe has made to the PNT strategy and informs stakeholders relevant to the development of resilient PNT policy and strategy, including:

- UK Government,
- Department for Transport,
- UK Space Agency; and
- UK PNT office.

## 5 CONTEXT FOR INTEGRITY IN THE MARITIME SECTOR

The PNT information displayed on a mariner's navigation system usually relies on satellite derived GNSS signals as the primary source of navigation, and is used for all facets of maritime operations and navigation.

GNSS is often supplemented by dead reckoning navigation systems such as inertial navigation, however this is subject to compounding drift errors so is not a sufficient fallback over sustained periods of time.

Other sources of PNT are emerging, such as eLoran, LEO-PNT, and VDES R-Mode, which will mean there could be less reliance on GNSS, however these have not been widely implemented into the maritime sector yet and therefore GNSS is currently still relied upon.

The Maritime sector contributed £48.9 billion of GVA to the UK economy in 2019 [35], supporting an estimated 1 million jobs across shipping, ports and leisure. Emerging maritime technologies, such as autonomy, remote operations and sea-traffic management are furthering critical dependence on PNT data, often in contexts with reduced human oversight.

This places a critical focus on the trustworthiness of PNT data in the maritime sector, further emphasised by the rapidly increasing complexity of the seascape due to traffic levels and the proliferation of offshore renewable energy and other infrastructure. This issue will be exacerbated by autonomy, where the concept of the 'mariner' may evolve, and the role of a human 'user' might be reduced; the ability to algorithmically estimate the validity of PNT data and a resulting navigation solution will be crucial. In navigation systems configured as systems of systems, faults can spread impact through the entire eco-system rather than being localised. In addition, systems of systems exhibit emergent behaviour where a fault of a single complement has a different, and broader impact than just on that component alone.

This highlights the urgent need for improved PNT resilience in general, and the specific and core requirement for significant improvements to maritime PNT Integrity Monitoring capabilities. Integrity monitoring provides the end-user or mariner an indication of the quality and trustworthiness of the PNT data they receive, which enhances navigational decision making and improves the safety and efficiency of navigation.

### 5.1 GNSS Signal Vulnerabilities

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GNSS signals are weak when arriving to earth, they are vulnerable to unintentional interference and to intentional disruption due to their low signal strength and requirement that different systems share common radio frequency bands, making them easier to jam. This can deny the user access to satellite signals meaning the vessel is unable to determine its exact true position [15].

#### 5.1.1 Unintentional disruption

##### 5.1.1.1 Satellite system faults – single and multiple:

Satellite system faults can affect both individual satellites and multiple satellites at system level, these failures can be caused by the space environment or space debris, interfering with the signal.

##### 5.1.1.2 Constellation faults:

Constellation faults can occur in two incidents. There may be a whole constellation ephemeris failure, such as a datum offset, or a clock offset may occur between whole constellations of satellites resulting in inter-constellation bias. Clock offsets represent the difference between what time the receiver thinks it is, and the true time, with the latter determined by the underlying GNSS atomic time scale.

#### 5.1.1.3 Ionospheric disruption:

It is possible for ionospheric storms (space weather) – the largest of which was the well-known Carrington event of 1859 – to impact on GPS and GNSS signals, this causes refraction and diffraction which can scatter GPS signals, distorting the information received by the receiver as waves come through multiple paths. This can result in a delay of the signal and an inaccurate determination of location due to the hazardously misleading information (HMI) [16].

#### 5.1.1.4 Local faults:

Local faults occur in the local (user-level) environment when conditions around the receiver affect the GNSS signals and impact navigation. Tall buildings and obstacles can cause both line of sight (LOS) multipath interference and non-line of sight (NLOS) reception. LOS occurs when the signals are blocked by buildings/obstacles and NLOS occurs when only reflected signals reach the receiver which will provide misleading information. The multipath effect in the maritime domain is caused by a combination of reflections from the sea surface and vessels, port cranes, bridges or other facilities, as such signal reflections can take place relatively frequently.

In addition, ships and ports can also be hostile electromagnetic environments, with strong in- and out-of-band broadcasts from systems, such as radars, which might interfere locally with GNSS signals. There are also many examples in the past of GNSS in harbour environments being disrupted by out-of-band emissions from, for example, television equipment and from GNSS jammers illegally employed for other purposes, like masking tachographs.

### **5.1.2 Intentional third-party interferences – Jamming/Spoofing**

Due to the low power of GNSS signals a weak interference source can cause the receiver to fail or give out hazardously misleading information.

Jamming and interference:

GNSS signals can be jammed by masking the satellite signal with noise, this is usually intentional aiming to overwhelm the weak GNSS signal [17].

Spoofing and meaconing:

Spoofing is the creation of false GNSS-like signals transmitted with the aim of misleading the GNSS receiver, resulting in a false position estimate [15]. Another, similar, spoofing method is to rebroadcast genuine GNSS signals captured at a different time, therefore leading to an inaccurate position. Without capable integrity monitoring these forms of interference can be hard to detect.

## **5.2 Key Drivers and Use Cases**

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The following sub-sections provide an overview of the use cases for integrity focusing on cases which increase the complexity of navigation for the user, the impact of signal interruption for the user and future maritime operations.

### **5.2.1 Traffic density and vessel size**

Maritime operations are becoming more complex and is due to increase over the next 5-10 years. Over the past decade, the number of container ships in the global fleet increased from 4,966 ships in 2011 to 5,534 ships in 2021 [2], as well as an increase in differentiation in autonomy levels on board vessels. Traffic density, and vessel size as shown in figure 2 and figure 3, is increasing in many areas and therefore reducing the room for manoeuvre and increasing the number of crossing and convergence points. Ships focus on taking the most economical route and therefore often take the same route as many other vessels. An increased number of ships taking the same route results in an increased concentration of

vessels making collisions more likely and impacting the safety of mariners, and potential cause of economic loss.

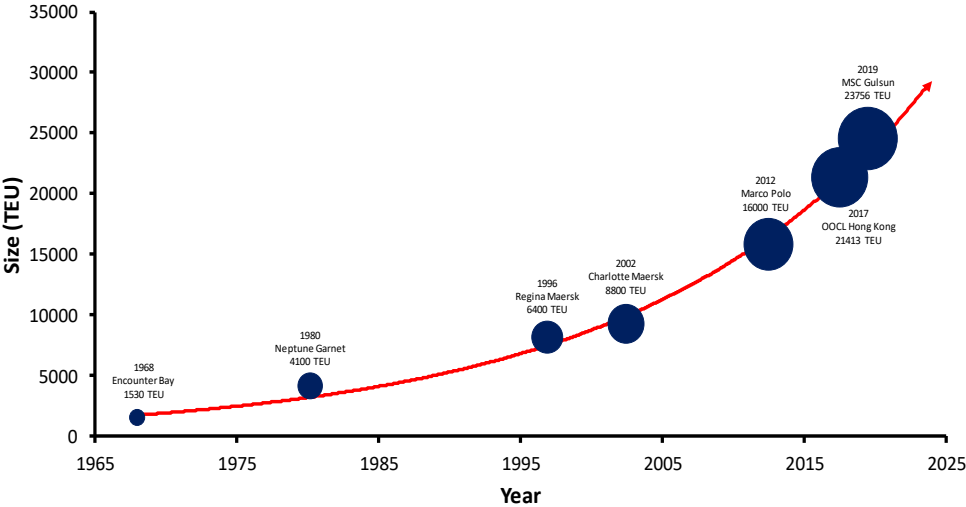


Figure 2 - Size of container ships

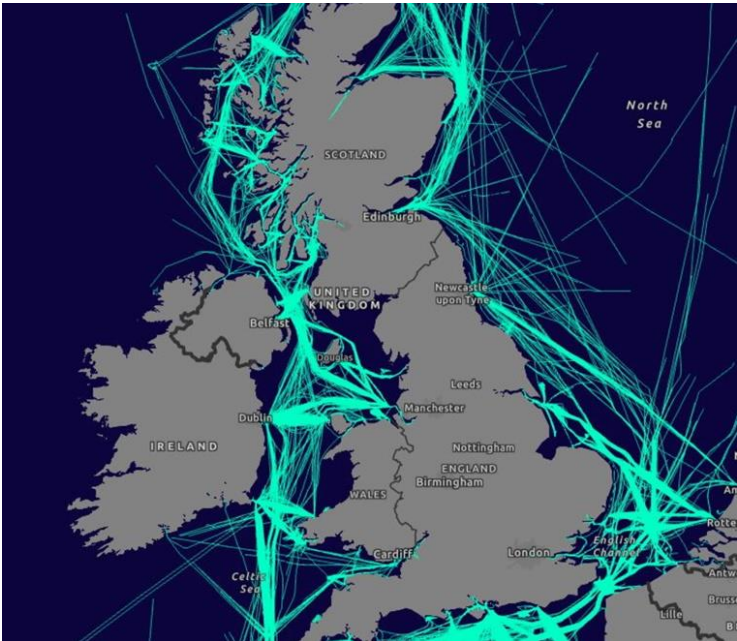


Figure 3 - Density of marine vessel traffic, UK, 2017, APBMer [3]

EMSA published its Annual Overview of Marine Casualties and Incidents for 2022, informing that 2,510 marine casualties and incidents were reported, involving 2,701 ships [4]. Between 2014 to 2022, 45.3% of the marine casualties and incidents took place while in the port area, 44.0% took place in mid-water or transit and 10.7% of casualties and incidents happened in unknown segments. If vessel size and concentration continues to increase then casualty numbers are likely to continue to increase, particularly in areas of congestion if mariners are not aware of the integrity of their navigation systems.

**5.2.2 Offshore energy – Oil, Gas and renewables**

An increase in offshore renewable energy production and other infrastructure is expected, taking up more space in UK waters, reducing the room to manoeuvre for vessels, and impacting safety. Between now and 2030 Britain’s offshore energy producers could spend up

to £200billion on new energy projects in the North Sea and UK waters suggesting huge investment in maintaining and operating offshore energy infrastructure [5] requiring marine vessels to complete this work.

The oil and gas industry has a vital role in the economy of the UK and accounts for more than 75% of the UK’s primary energy needs [6]. Almost 100% of UK oil and gas production is extracted from multiple offshore fields all over the UK. More oil fields and wells will need to be established in the future to maintain the required volumes to meet the needs of the UK, these will be set up, operated and maintained by marine vessels, in some cases with autonomous systems already being used for monitoring aspects of operations. For further benefits to offshore oil and gas rigs to be realised from advances in vehicle autonomy, precise and trustworthy position data is required for vessels to operate safely in the complex environment.

UK geography creates a beneficial environment for the growth in production of offshore wind energy. The UK has potential to have up to 50GW offshore wind capacity by 2030 (including 5GW of floating offshore wind) [7]. Figure 4 shows planned future investment in offshore wind in the UK, 60% of this pipeline is fixed and 40% is floating highlighting the increasing level of complexity for safe manoeuvres particularly as wind farms increase in size. Autonomous vessels would bring benefits throughout the operations phase, carrying out remote inspections and potentially performing maintenance work in the future.

**Current Offshore Wind Pipeline (GW)**

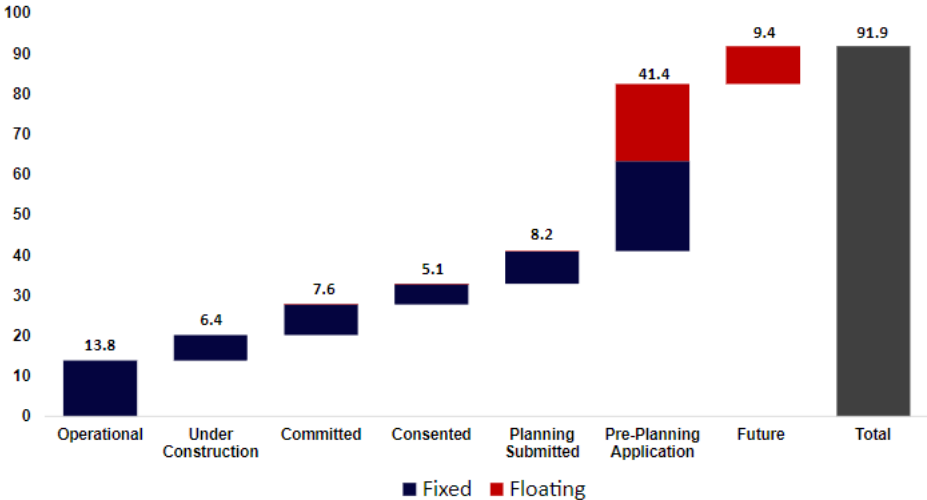


Figure 4 - Current UK Offshore Wind Pipeline (GW), Gov UK [7]

Increasing offshore energy obstacles alongside the increase in vessel numbers and size will present new challenges for the user and the safe navigation of vessels due to the reduction in sea space, resulting in a greater requirement for high integrity PNT data.

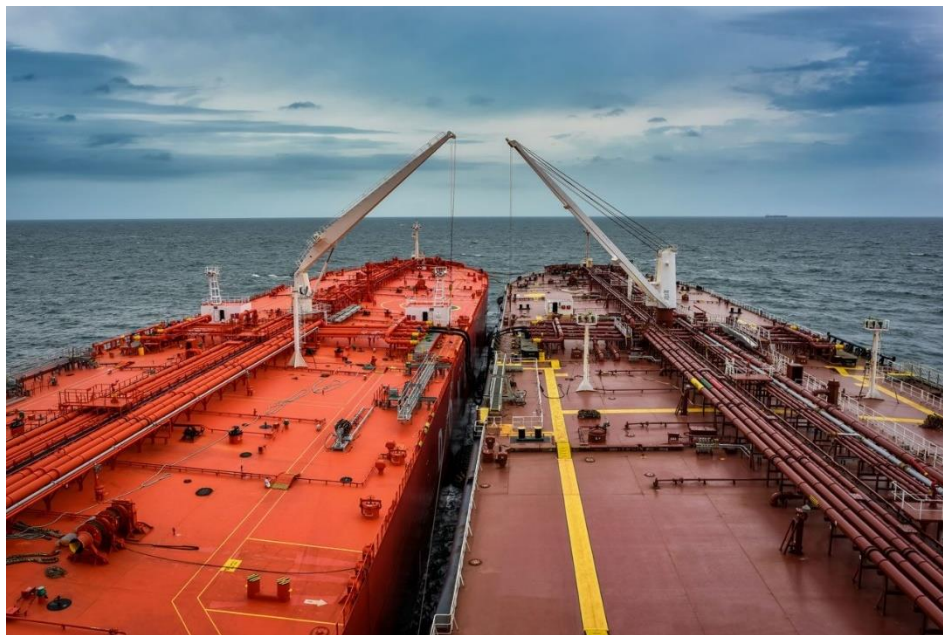
**5.2.3 Aquaculture**

Aquaculture is the farming of aquatic plants, animals and other organisms for commercial, recreational and scientific purposes, enhancing the natural supply and contributing to the UK food supply. In 2019 almost 234,000 tonnes of farmed food fish was produced through aquaculture [8]. UK aquaculture will help to secure seafood supplies and encourage investment and economic growth along the UK coastline. In 2018 approximately 3,000 FTE jobs were directly provided through aquaculture and the industry produced £972m in income in the UK [9].

Marine vessels rely on PNT information to carry out a number of key activities, such as feeding, monitoring conditions and dealing with hazards, to support the planning, management and development of aquaculture farms. This is a difficult environment to navigate around and with future automation of these activities to improve efficiency and worker safety, it is crucial that integrity information is understood to prevent accidents.

#### **5.2.4 Ship-to-ship transfers**

Ship-to-ship transfers allow for larger ships to offload cargo to a smaller vessel to offload the cargo to help in more restrictive ports, lightening a vessel or refuelling ships. Transfers can happen at sea or in port and the operation is essential for the UK's energy security and supply chain.



*Figure 5 - Ship to Ship transfer [36]*

Although safety standards are in place there are serious risks that may arise if an accident or collision occurs during transfer. Safe transfer operations therefore rely on being provided with correct and trustworthy PNT data to understand the positioning of both vessels. Misleading positioning information may lead to fatal accidents and spills causing environmental pollution.

#### **5.2.5 Fisheries**

Fisheries account for all activities involving the collection of wild aquatic life, aside from farming of fish, and also play a crucial role in the UK economy and food production. In 2022, UK vessels landed 640 thousand tonnes of sea fish into the UK and abroad with a value of £1.04 billion [10].

Labour supply is emerging as a serious risk to this industry, the total number of fishers in the UK was approximately 11,000 in 2021, which has decreased by almost 10,000 since the mid-1990s [11]. A shrinking workforce may escalate the reliance on automation within the industry which can be used in multiple activities such as environmental monitoring sensors and blockchain technology that improves transparency, traceability, and automates some customs checks. Automation will also improve the safety of operations through reducing the time at sea workers have to spend facing the harsh environmental conditions.

### **5.2.6 Bio-economy**

The bio-economy includes all economic activities and industries that utilise biological resources found in the marine environment. In the UK Marine Protected Areas (MPAs) are set up similarly to a national park, with their aim being to ensure wellbeing of marine plants and animals and their environments.

In 98% of UK MPAs trawling and dredging is taking place having negative environmental and economic impacts [12]. Marine vessels, in particular autonomous vessels and sensors, have the opportunity to provide an important source of data in monitoring and the surveillance of MPAs to police these activities. Vessels need to understand the integrity of the navigation data to effectively carry out these operations and to ensure they themselves do not impinge on the protected areas, causing further damage.

### **5.2.7 Carbon Capture and Storage (CCS)**

To support in achieving the UK's 2050 net zero commitment one contribution is long term storage of CO<sub>2</sub> emissions underground with seabed reservoirs used in some locations. CCS will be able to safely store up to 78 billion tonnes of CO<sub>2</sub> under UK sea-beds and could help to boost the economy by up to £5billion per year by 2050 [13]. To exploit this capacity much of the development and operational activities are going to take place at sea using vessels to drill and evaluate sites to be used to place rigs and equipment. Live positioning information will be required to ensure that the rig remains within distance of the well for operation. Integrity alerts will be required to notify when navigational data may not be trustworthy and incidents may occur.

In the future integrity information will be vital for autonomous systems which may be used to replace workers in dangerous conditions as well as improve the response from Search and Rescue (SAR).

### **5.2.8 Ocean energy**

Ocean energy is one of the world's largest and unused sources of renewable energy derived from waves, tides, currents and thermal gradients. The UK has huge potential to exploit ocean energy given the extensive coastline and access to both tidal and wave energy.

It is estimated that the UK has around 50% of Europe's tidal energy resource which has the potential to produce 20% of the UK's current electricity demand [14]. To exploit these energy resources a new range of infrastructure will be required in UK oceans. This will increase the number of objects to be avoided by vessels and complexity of navigation for mariners increasing their need to rely on trustworthy PNT information.

### **5.2.9 Summary**

The maritime industry relies on trustworthy PNT for all core marine operations including but not limited to, search and rescue missions, maintaining and operating off-shore energy supplies, sea food production and farming and movement of cargo which all have an influence on the UK economy. PNT data is extremely important for the UK as the economic impact of a 5-day loss of GNSS would cost the UK maritime economy over £1billion [15]. This demonstrates the need to be able to determine the integrity of the navigation data and for vessels and mariners to trust the navigation system.

## **5.3 Need for Integrity**

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### **5.3.1 Current Maritime Operations**

Maritime operations are not the same for all journeys and vary greatly. This increases the complexity in maritime operations which typically include the following phases:

- The Ocean Phase – position fixing by visual reference to land, or to fixed or floating aids to navigation is not possible.
- Coastal Navigation – within 50 nautical miles of the coast or at the limit of the continental shelf. The principal uses of navigation systems in this phase of voyage are associated with maintaining safety.
- Port approach and restricted waters – freedom to manoeuvre is limited requiring active traffic management and navigation requirements are more stringent.
- Docking/Port – the proximity of ships to port facilities making the use of radio-navigation aids impractical. Adjacent structures may obscure signals and large metallic objects can cause multipath, plus problems caused by electromagnetic interference.
- Inland waterways – operations involving large, slow vessels in high traffic areas with limited manoeuvrability.

In these operational phases GNSS is the common source of vessel PNT data. It is important that in all these different phases of operation that the mariner or vessel can trust the PNT data to ensure safe navigation, particularly in areas of dense and complex traffic, and therefore being notified of system integrity is vital for the mariners who are carrying out these manoeuvres within each different phase.

### ***5.3.2 Future Maritime Operations***

As detailed above, there are many opportunities where autonomy would be beneficial in the maritime sector to improve efficiency, make operations safer and enhance SAR missions to name but a few.

Technological innovation and advancement within the maritime industry is resulting in an expected rapid expansion of autonomous vessels [18], remote operations, sea-traffic management, vessel size, vessel digital twinning and connected just-in-time logistics which will have greater operational need on PNT data, often in contexts with reduced human oversight, therefore increasing the importance of integrity monitoring.

In some sea areas, autonomous and remote-controlled ships are already being trialled. Success of these trials could lead to much safer operations, however the level of risk or liability must be clearly allocated for remotely piloted vessels, and its implementation should be validated. The UK Government has launched Maritime 2050 which sets out the agenda for the UK to develop a legislative framework for autonomous vessels and seeks to promote smart shipping and autonomy to improve the UK maritime sector [19].

Autonomy within maritime vessels will not only be seen in fully autonomous vessels, but also in autonomous support systems and remote control of vessels. These systems will rely on multi sensor PNT solutions to provide resilience and mitigate against the loss of having the mariner as the final decision maker.

## 6 INSPIRE METHODOLOGY

Throughout INSPIRe a number of research and development activities have been completed and integrated to develop a maritime integrity solution.

INSPIRe adopted the following approach:

- State-of-the-art review of integrity monitoring approaches.
- Development of high-level system requirements specification for maritime integrity monitoring.
- Development and testing of integrity monitoring approaches and algorithms, both at the user-level and the system-level.
- Verification and validation of integrity approaches.
- Stakeholder Engagement conducted throughout the project to align integrity approaches and understand the maritime sectors requirements.
- Complete a Cost Benefit Analysis which considers each INSPIRe integrity concept with their ability to provide integrity information for each use case defined.
- Development of an implementation and exploitation plan, providing a roadmap with required work activities to mature the integrity concepts.

Initially a state-of-the-art review of current integrity monitoring approaches was carried out. It focussed on both maritime integrity monitoring algorithms at the user level and approaches used by the aviation sector, which has historically led integrity monitoring development driven by stringent safety requirements, and drew out areas of similarity and difference between them. Further details can be found in Section 8.

Based on this review as well as key standards, a high-level system requirements specification for maritime integrity monitoring at the system- and user-level was developed. These requirements were written to be implementation agnostic, providing scope for both convention and novel integrity monitoring approaches to be developed by the INSPIRe consortium. They were also validated against known sector use-cases (derived from MarRINav) and directly with the end-user community.

Following this, the INSPIRe project explored and developed integrity monitoring approaches for the maritime domain. Algorithms for single-frequency and dual-frequency multi-constellation GNSS integrity monitoring were developed, this included both approaches focussed on rapid near-term deployability, and more complex methods closely resembling the state-of-the-art in aviation but being further from deployment readiness. These integrity approaches were also expanded beyond GNSS derived PNT to a generalised vessel autonomous integrity monitoring (VAIM) approach, integrating inertial measurement (dead reckoning) inputs and open to other additional PNT sources. INSPIRe also examined the benefits a maritime specific SOLAS (SBAS) message could provide to improve the user-level integrity solution, and developed a prototype RAIM availability prediction tool to enable the maritime end-user to predict integrity monitoring performance throughout the UK EEZ. Further details of the user-level segment and algorithms are provided in Section 10.

Approaches to system-level integrity monitoring were also developed by the INSPIRe project, focussing on system-level EGNOS monitoring and UK-based DFMC integrity monitoring. A set of potential monitoring requirements were developed and a simple EGNOS monitor is proposed, similar to the WAAS User Position Monitor trusted by the FAA. The DFMC Integrity Monitoring (DIM) Service proposed by INSPIRe provides system-level integrity assurance for maritime DFMC users in the UK EEZ. Further details of the monitoring software developed is provided in Section 11.

The integrity approaches developed by INSPIRe were verified and validated against the requirements the project developed and an overarching list of maritime use-cases. Integrability of the solutions was also a key aspect of this project, and common implementation and integration requirements served to ensure that all the solutions

developed could be brought together into a systems-of-systems integrity solution to provide an improved integrity monitoring capability to the mariner.

Stakeholders were engaged with throughout the project to consider the maritime sectors understanding of integrity and consider their input into developing the use cases and integrity requirements. In February 2023 a stakeholder event was held with a number of senior leaders and experts in the maritime, navigation and related sectors to gather their understanding of integrity and its importance. Other projects were engaged with to provide awareness to both teams on the aims, objectives and development progress. INSPIRe held meetings with both the TREN project team in October 2022, who developed a GNSS receiver for railway safety-related applications to demonstrate resilient PNT according to railway standards, and multiple meetings with the UK SBAS project team who are developing a UK specific SBAS as an alternative to EGNOS to understand the feasibility of such a system for the UK and their understanding of integrity.

The results from the above activities have driven the development of outputs by providing validation of the set of use cases, integrity algorithms and scenarios for the Cost Benefit Analysis and the Implementation and Exploitation Plan.

A Cost Benefit Analysis (CBA) based off the outcomes and results of the integrity algorithms, systems and use cases was completed. The CBA considers use cases in the maritime domain which were drawn from the systems engineering and stakeholder engagement workstreams of INSPIRe. The CBA considers each INSPIRe integrity concept with their ability to provide integrity information for each use case defined. A more comprehensive breakdown of the CBA and the results is provided in Section 13

The implementation & exploitation plan consolidates the implementation requirements and roadmap for the system-level integrity concepts and the RAIM Performance Prediction tool. INSPIRe produced a roadmap to develop user-level standards for maritime, including how the user-level integrity concepts can be used to support this process and opportunities for maritime operators and users, receiver manufacturers and government to exploit the integrity concepts for maritime which have been identified. INSPIRe also identified opportunities to expand integrity concepts to use cases with high performance requirements and across sectors outside of maritime are identified and external factors considered. Further details can be found in Section 12.

## 7 STATE OF THE ART REVIEW

A state-of-the-art review and consolidated the current situation regarding maritime integrity, and previous activities that have investigated approaches for integrity in the maritime domain was completed. This section of the report highlights the main outcomes from the review.

This review looked at the existing integrity monitoring solutions used in the aviation domain and those currently applied in the maritime sector. The study reviewed the requirements set out by the governing bodies of both sectors, and it has been observed that both sectors' definition of integrity is in alignment, however the requirements guiding the performance standards of these sectors are quite different. For instance, within the maritime requirements there is generally no need for the vertical position component as there is within aviation, and this shows as a clear difference between the maritime and aviation domain which impacts on the design of the integrity algorithms.

In the maritime domain, the current requirements are linked to system integrity and do not cover user-level integrity and the associated additional faults which may exist for a receiver on a vessel. Currently no well-defined and up to date values for the alert limits and integrity risk at each operational phase within maritime exist, unlike in aviation. At present, the only clear requirement within maritime is the need to raise alarms at the presence of faults, yet this still relies on the mariner to be able to collect all the navigation information available and then make a decision.

Within aviation there is also a well-established regulatory framework with many institutions collaborating, each of them with a clear role in terms of regulation development, certification, inspection, licenses issue and punitive capacity. A similar basic structure is applied within the maritime domain although roles and responsibilities are not as prescriptively defined as in aviation and there are sometimes overlapping responsibilities between organisations and different structures in different countries.

### 7.1 Understanding of integrity and risk – Maritime vs Aviation

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Aviation performance standards provide well defined concepts, procedures, allocation and understanding of failure risk. Aviation has stringent and extensive regulation because several key processes for flight safety take navigation information as inputs and the risk of accident is required to be allocated in a top-down approach. However maritime performance standards are largely based on judgement and mostly modelled on and adapted from aviation standards. For the maritime current situation, the mariner makes the final decision on navigation, informed by from multiple sensors, charts, visual aids and various information services. The failure probability allocation has never been considered in this context.

Civil aviation has traditionally been the driver for the development of the GNSS integrity concept. However, it is important to highlight that although the concept of integrity is very similar in the maritime communities, the operational contexts are different and it is not possible to port existing aviation integrity solutions directly into maritime applications. Therefore, the aviation safety approach cannot be directly used in the maritime sector, partly due to its rigidity and computational complexity. Straight-forward application of an aviation SBAS-like integrity concept is not suitable for the maritime community and/or is not in line with the ones proposed in the maritime community. Therefore, special attention must be paid to understanding maritime community safety needs and timeframe considering SBAS/aviation design considerations and translating them in terms of integrity.

### 7.2 Comparing aviation and maritime operations

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In controlled airspace, there is a small number of aircraft configurations as access, vehicles, operations and onboard equipment are tightly regulated. Aviation operations are less tightly controlled in uncontrolled airspace but, even then, vehicles, crews and onboard equipment are still tightly regulated and subject to certification and licensing. In most cases, the

maritime sector does not differentiate between different types of sea-space: rather than being segregated all vessels – supertankers to rowing boats – can operate in the same area and the diversity of operations, vessel capabilities, onboard equipment and crew capabilities is much higher than for aviation.

In aviation, in controlled airspace, each flight phase and type of approach have well defined requirements and a clear relationship with tolerable collision risk and the classification of the airspace and operation. In maritime, there is a much wider range of operations taking place in the same vicinity and many of them very different performance requirements. This means the same system in the same place will comply with the performance requirements for some operations and not others. The maritime operation phases are described in Section 7.

There is also a difference between the exposure periods where integrity and continuity are specified. In aviation these are defined over a period of 150 seconds for integrity and 15 seconds for continuity, whereas in maritime the exposure periods are much longer at 15 minutes. This means that the number of integrity threats to be considered for maritime will be larger compared to aviation. It is also much more challenging to maintain integrity and continuity over longer periods of time.

### **7.3 MarRINav approach to M-RAIM**

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As part of the MarRINav project a modified, maritime specific approach for integrity was investigated (MarRINav M-RAIM). This is an adapted version of the aviation RAIM (ARAIM), developed to preserve maritime integrity and continuity performance requirements.

Both of these integrity algorithms can detect and mitigate a wide variety of different faults, including when multiple faults or failings are occurring simultaneously.

If many potential simultaneous faults are considered, then the number of combinations of different kinds of faults can be extremely high resulting in significant computational cost in the receiver.

Some of the disadvantages of the current MRAIM algorithm are highlighted below.

- The algorithm is computationally demanding due to the calculation of large quantities of subset solutions, this is dependent on the number of simultaneous faults and the number of satellites in solution. As the number of usable GNSS constellations increases, this may become a serious burden on the processor.
- The process is critically dependent on a-priori assumptions, both of the nominal fault free error models, and the assumed fault probabilities. Both of these should ideally be conservative descriptions of the real-world errors and risks involved.
- Evaluating the fault probabilities will depend on very long-term data collection and the choice of fault-free error models.
- The process for determining the cut-off for allocating monitored and un-monitored faults is not yet determined.
- For the MRAIM operation to be compatible with existing or future augmentation systems, the data produced by these systems must be given as fault-free estimates, appropriate to a given fault probability.

MarRINav suggested the three most well-defined gaps in maritime integrity are:

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

INSPIRe has defined a list of long-term maritime integrity needs, based on the current situation which aims to close the gaps between and bring immediate benefit to the maritime community.

## 8 REQUIREMENTS FOR THE INTEGRITY CONCEPTS

This section of the report provides an overview of the requirements developed for the INSPIRe integrity concepts and the approach, also covering aspects of Security and Safety analysis and the verification and validation process which was carried out throughout the project.

### 8.1 Requirement development

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A set of core top-level integrity requirements were developed which were applied as a requirements framework for both the user- and system-level integrity solutions to be developed against under the INSPIRe project. These requirements ensured that the technical solutions developed were consistent, could interface correctly and were integrable with one another.

The requirements were based on outcomes of MarRINav but were then refined throughout the INSPIRe project via technical input and stakeholder engagement activities. Future requirements were also presented as 'stretch goals': these suggest the possible trajectory of requirements as the maritime sector aspires to future use-cases such as widely deployed autonomous systems, as well as stakeholder 'needs' that go beyond traditional integrity monitoring but may have a place in next-generation or generation-after-next systems.

#### 8.1.1 Requirements capture

Initially the requirements were captured and filtered from the MarRINav project and have been consolidated and sectioned into the following categories based on the Holistic Requirements Model:

- A – Operational Requirements
- B – Functional Requirements
- C – Non-Functional Performance Requirements
- D – Non-Functional Systems Requirements
- E – Non-Functional Implementation Requirements

The A requirements provide a Concept of Operations (ConOps) for an integrity solution, based primarily on extant standards and official definitions. These are further supported by core requirements in the B, C, D and E requirement structure to describe the functional, performance, systems and implementation requirements respectively, providing granular high-level requirements for a GNSS integrity monitoring system without implying technical implementation.

INSPIRe has clearly labelled when requirements are only applicable to user-level or systems level solutions by assigning an applicability flag in the requirements list. Although a requirements list has been developed, some requirements remain incomplete due to the need for a deeper understanding of maritime fault probabilities and integrity events to allocate metrics of performance and risk.

In addition to this list, a set of future requirements has also been defined that relates to potential future situations where the maritime industry may rely further on resilient PNT, such as in autonomous vessels. Throughout the project these were not essential to be applied to all the technological solutions developed but would enable INSPIRe to highlight opportunities and barriers to relevant further development of integrity solutions.

The requirements have been reviewed and refined by both internal and external stakeholders. Internally this ensured that the requirements were consistent, feasible and suitable across the technical scope of the project, there were no gaps in the requirements and ensure the challenges of implementing a resilient PNT system were considered early on. The internal review also ensured all technical domain experts could have input and integrate further findings and knowledge not captured in MarRINav.

The external review focused on ensuring the integrity requirements and solutions are relevant and useful to the maritime and PNT communities. A list of relevant stakeholder engagements is included in Appendix A.

After initial requirements development, the integrity concepts were developed and validated. After this the requirements were reviewed and adjusted based on the validation results to ensure the requirements aligned. This led to a successful requirements development and resulted in a requirements set suitable for informing the development of our system- and user- level work packages.

This requirements set would benefit from future development to remove remaining ambiguities and to define a clear set of performance requirements feasible in, and appropriate for, the maritime domain. This activity would ideally be carried out alongside standards development, which needs renewal in light of current and future use-cases, and informed by our growing understanding of the art-of-the-possible in maritime integrity monitoring.

The requirements specification can be found in S-062-001-001.

## **8.2 Use Case Development**

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The use cases captured in INSPIRe describe how the integrity concepts may be used in maritime applications. The use cases have been classified according to the integrity need and positional accuracy requirements defined by MarRINav by aligning each use case to the voyage phase performance bands used the IMO A.1046 and A.915 resolutions.

The performance bands used are as follows:

- Performance Band A – Ocean phase (100m+)
- Performance Band B – Coastal-to-ocean phase (10m-100m)
- Performance Band C – Port-to-coastal phase (1m-10m)
- Performance Band D – Better than port phase (<1m)

The integrity solutions are validated through the verification and validation (V&V) process for each performance band. This approach permits a wide range of maritime use cases to be considered using a unified requirements set.

## **8.3 External Stakeholder Validation**

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External stakeholder validation was carried out to ensure the requirements, use cases and safety and security analysis are relevant for stakeholders in the maritime and PNT communities.

A review of the initial requirements and uses cases was completed with ESA and UKSA to validate the projects approach to the requirements development and provide an opportunity for their feedback.

Wider stakeholder engagement was completed to identify non-technical requirements such as information presentation. The use-cases considered by INSPIRe cover diverse maritime activities with relevance to numerous sectors which all have different integrity needs, therefore this engagement was important for the project.

The results of the stakeholder engagement activities have included:

- Developing links with the TREN EGSS-R, OS Net and UK SBAS projects to establish a common understanding of wider integrity needs;
- Validating that the use-cases used by INSPIRe remain contemporaneous, and that the performance-band approach provides suitable granularity;
- Investigating the needs of mariners when interfacing with vessel systems;
- Identifying the needs of insurers, GNSS/PNT system providers and government entities; and,

- Improving understanding of 'future' integrity requirements, including the potential demand for more stringent performance requirements, and also the stronger linking of PNT integrity to wider data integrity concepts as critical information sources broaden and connectivity demands increase.

#### **8.4 Verification and Validation Process**

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The verification and validation process was applied to assess how well the technical solutions developed under INSPIRe meet the defined requirements of an integrity solution. It was not expected that all solutions developed under INSPIRe would meet all of the requirements, however this process allows for strengths and limitations to be assessed and provide an understanding of how achievable the proposed requirements are for future development of integrity solutions.

#### **8.5 Verification and Validation Results**

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For each technical solution the V&V results were recorded and reviewed to ensure that all requirements have been interpreted consistently, responses were complete and correct, non-compliances were justified and the results from the technical solutions aligned with their intended goals in the context of the overall INSPIRe project.

Some of the integrity solutions developed under INSPIRe may not meet all specified functional or performance requirements. These non-compliances are seen as an opportunity to define and overcome the barriers to developing functioning integrity solutions. A number of approaches are used to manage non-compliances to understand why the requirement is not met and if changes are required.

Each technical report contains a detailed analysis of the V&V results and a summary is provided in the Systems Engineering Report.

The top-level requirements set includes compatibility requirements to ensure that the integrity solutions proposed are compatible between the system- and user-levels. INSPIRe has worked to facilitate knowledge exchange across development of each technical solution to ensure consistency and the development of compatible integrity solutions which can be brought together.

## 9 USER LEVEL INTEGRITY CONCEPTS

The following section provides an overview of the technical solutions developed in INSPIRe. Firstly, the user-level algorithms are discussed as well as the performance availability tool. This is followed by an overview of the system-level integrity monitoring solutions, the approach to developing these and the outcomes.

### 9.1 User Level Algorithms

#### 9.1.1 GPS MG-RAIM integrity solution

##### 9.1.1.1 Overview

INSPIRe algorithms have been explored, developed and tested to provide user-level integrity for single frequency GPS, considering the two maritime scenarios: the first where system level integrity information is available (maritime RAIM [MRAIM]), e.g., from existing EGNOS V2, and the second where there is no system level integrity information to facilitate the onboard processing, (maritime general RAIM (MGRAIM)). The need for a maritime specific Space-based augmentation system (SBAS) message to assist in the user-level integrity solution was also examined.

The following subsections describe the high-level algorithm design, development and testing of the algorithm, the outcomes from the algorithm development and its benefits and disbenefits.

##### 9.1.1.2 High-level design for the GPS M(G)RAIM integrity algorithm

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

The algorithm is based on two sequential steps once the position is calculated with all the available satellites.

- Availability check: A set of simple checks are applied to determine whether the derived all-in-view solution is suitable for navigation as defined by the maritime receiver specifications. If any of these tests fail, then an integrity alarm is raised.
- Fault detection: If all the previous test meets the defined conditions, a Chi-Squared test is performed to identify a fault in the positioning estimation.

Geometry screening: For each potentially faulty element of the navigation solution, a subset navigation solution is formed by eliminating the faulty element from the all-in-view solution. Then, availability checks are performed to check if the remaining solution would pass, to determine if the detection capability of the solution is sufficient

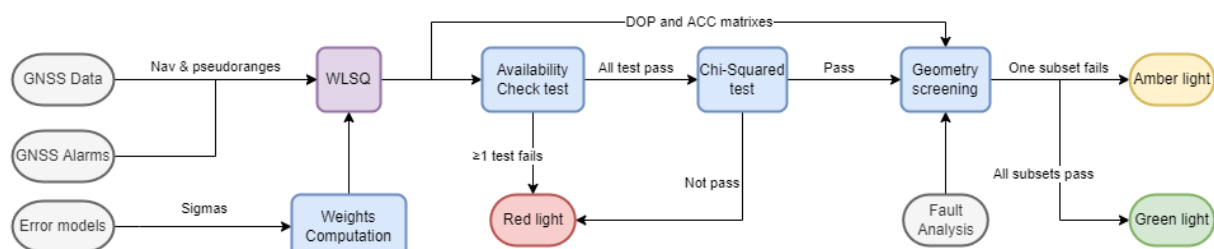


Figure 6 - MG-RAIM conceptual flowchart without augmentation

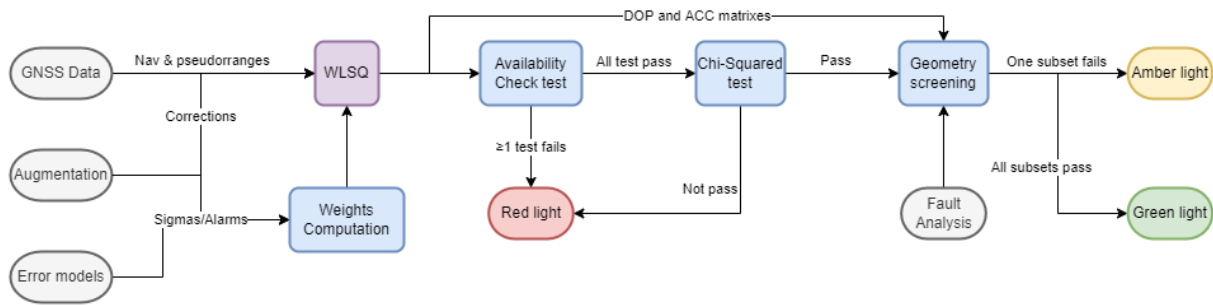


Figure 7- MG-RAIM conceptual flowchart with augmentation

Where:

- Grey bubbles are the required inputs
- Purple box is the PVT engine which computes the user estimated state vector
- Blue boxes are the functions involved in the integrity algorithm
  - Weights computation: computes satellite error models considered as nominal for the maritime environment.
  - Availability Check Test: the function that checks if the current solution is suitable for maritime in terms of expected accuracy.
  - Fault Detection, Chi-Squared test: function that detects if solution complies with the nominal error models.
  - Geometry screening: function that identifies the potential failure and performs additional tests to measurements subsets.
- Red, amber and green light bubbles are integrity warning output information provided to mariners;
  - Red light: provided to the mariner when at least one of the availability check or the fault detection test do not pass.
  - Amber light: provided to the mariner when geometry screening raises an alarm for at least one subset
  - Green light: provided to the mariner when all the tests are performed successfully, and the solution is therefore suitable for navigation.

### 9.1.1.3 Navigation Solution

We consider the mathematical process of deriving a position fix from a set of pseudo-range measurements. Each measurement equals the range to the satellite, plus a common receiver clock-offset, plus some measurement noise.

Because of the existence of this noise, the solution is to guess the user's approximate position linearising the problem. This is known as Least Squared estimation and is the core of the navigation solution estimation.

This algorithm uses models of the estimated (fault-free) variance of each pseudo-range measurement to provide a most accurate position. However, these models will be key for algorithm integrity.

The algorithm is able to provide the co-variance estimate which can then be used to estimate the 95% accuracy of the resulting solution. The usual estimation takes into account the less optimistic estimate (especially in case of high DOP) using the elliptical formula to take into account that maximum uncertainty does not necessarily be aligned with the east or north component.

Finally, the DOP matrix provides an indication of how a positioning error is affected by satellite geometry for each component. In this algorithm is required to compute the horizontal and geometric dilution of precision (DOP).

#### 9.1.1.4 Availability Check

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

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

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

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

#### 9.1.1.5 Fault Detection Test

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

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

These thresholds are pre-computed to provide a controlled risk of false alarm, per independent sample, of  $10^{-5}$ . This is to ensure that the continuity requirement 99.97% per 15 minutes can be met by the system<sup>1</sup>.

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

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

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

#### 9.1.1.6 Geometry Screening

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

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

If the subset solution is, then also “suitable for navigation” as described in 0 then this is indicative that RAIM will have adequate geometric detection fidelity to flag this fault before it

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<sup>1</sup> This False Alarm probability is an INSPIRE assumption, proposed in MarRINav

becomes excessively large. Any likely fault for which adequate detection fidelity is not guaranteed is grounds for raising the “amber light” caution.

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

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

We note that this is an arbitrary decision threshold and holds no bearing upon an agreed level of integrity performance, or error bounding. However, it does agree with the wording in the extant maritime receiver performance standards 0. A method of screening geometries to eliminate unsafe solutions (for which a substantial fault may exist un-detected) is necessary for the safety of the “green light” guarantee passed to the mariner.

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

9.1.1.7 Summary

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

Table 1 -Summary of Maritime Integrity algorithm output states

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

9.1.1.8 Outcomes

The performance of the developed algorithm was evaluated to determine its suitability and to identify areas for further development and investigation. The experimentation results have shown for some real data and example faults the fault detection capability of the MGRAIM developed for GPS L1 and GPS L1 + EGNOS processing. Those tests validate the functionality of the algorithm and compare the detection capability of GPS and GPS+EGNOS cases for different types of faults.

To evaluate the algorithm’s ability to detect faults simulated data was used where the faults were injected into the RINEX file. The simulated data provided an option to cover scenarios that would otherwise not be possible using field data alone.

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

After the suitability assessment, further analysis of the integrity algorithm's performance was conducted using Monte Carlo simulations, with the objective of appraising the feasibility of the algorithm's performance during each navigation phase.

In these Monte Carlo simulations, we present additional analysis to evaluate the algorithm's performance and identify the algorithm's strengths and limitations.

#### 9.1.1.9 Benefits and disbenefits of the integrity solution

Overall, these results show for the MGRAIM algorithm that:

- In the fault-free case, GPS L1 alone can meet the performance requirements for the ocean case (100m accuracy).
- GPS L1 alone cannot meet the coastal performance requirements (10m accuracy) because 18% of sample epochs are marked either as red or amber. This is because the computed 95% horizontal accuracy of the all-in-view and/or subset solutions is larger than 10m in many cases.
- The use of EGNOS does allow the coastal performance requirements to be met in fault-free case (for the scenario analysed) because the actual range errors (and assumed errors models) are smaller in the EGNOS case.
- The fault detection part of the MGRAIM algorithm can detect many cases where the range errors are excessive and help protect against the largest position errors that would occur.
- Fault detection performance is better for the case with EGNOS compared to GPS L1 only, as the expected errors are smaller so faults can be detected at smaller values, and so undetected position errors are smaller than in the GPS only case.
- In faulty cases it is noted that the computed 95% horizontal accuracy value is not a good indicator of actual horizontal error, and around 30% of the actual errors are bigger than the computed 95% horizontal accuracy.

It should be remembered though that these results and conclusions are very dependent on the assumptions used in the generating the data. In particular:

- The fault free performance against requirements is completely dependent on the assumed values for the error models. If it is found that the error models need to be larger or smaller to represent the true errors then this will have a direct impact on the computed 95% accuracy values.
- The representativeness of the reported 95% horizontal accuracy values, and the fault detection performance, is very dependent on how accurately the error models represent the actual errors. This can be clearly seen in the faulty cases where the reported 95% accuracy is no longer a good estimate of the actual error in the position solution. This means that it is critical that validated error models are defined for use in the actual algorithms on receivers – and for further validation activities.

#### 9.1.1.10 Maritime Specific SBAS Message

Finally, the need for a Maritime Specific SBAS Message was assessed. The work undertaken aimed to explain the integrity provision of the SBAS maritime system, focusing on expected developments and detailing the current SBAS status to analyse the need for a maritime-specific EGNOS message.

As evidenced by the findings of the algorithm assessment and performance analysis, the proposed integrity algorithm does not necessitate the introduction of any additional SBAS messages or modifications to existing ones. Current SBAS messages can be employed seamlessly with a dedicated maritime receiver implementation, where certain messages may be selectively utilized. Moreover, to accommodate varying integrity requirements at the user level, distinct scale factors can be employed to calculate Protection Level.

However, there is potential optimisation of SBAS services for maritime. Service monitoring system is based on aviation and its requirements for integrity and accuracy, therefore

overbounding sigma errors could be inflated with respect to the requirements for maritime. In addition, healthy checks are also driven by aviation requirements and satellite healthy flags may be different for each transportation domain. Nevertheless, this optimisation may imply to duplicate the ground segment processing chain and the performance improvements may be small. Because of that, this trade-off should be carefully assessed due to its technical and economic implications.

Should the trade-off analysis indicate the need for a new maritime SBAS message, it is anticipated that any potential new SBAS message would be designed in accordance with the following requirements, with their specific values determined on a case-by-case basis.

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

### **9.1.2 DFMC M(G)RAIM integrity solution**

#### **9.1.2.1 Overview**

The DFMC M(G)RAIM integrity solution built upon the work carried out in the previous section to investigate, develop, and evaluate algorithms for dual frequency multi-constellation GNSS integrity, once more considering both scenarios: with (MRAIM) and without (MGRAIM) dual frequency multi-constellation system-level integrity information (potentially supplied by a future EGNOS V3).

This integrity solution investigated, developed, and tested dual frequency multi-constellation integrity monitoring to define the SBAS support data necessary for MRAIM implementation, evaluate the feasibility of providing that data, and conduct the required trade-offs.

The following subsections provide a high-level design and description for the DFMC integrity algorithms and the findings found through development and testing.

#### **9.1.2.2 High Level DFMC M(G)RAIM Algorithm Design**

The maritime integrity algorithm proposed for M(G) RAIM is based on a Classical RAIM algorithm, used for decades in maritime receivers, that is applied to the overall solution and to measurement subsets to ensure the fault detection (and exclusion if needed) capabilities.

The algorithm is based on two sequential steps once the position is calculated with all the available satellites.

- **Availability check:** A set of simple checks are applied to determine whether the derived all-in-view solution is suitable for navigation as defined by the maritime receiver specifications. If any of these tests fail, then an integrity alarm is raised.
- **Fault detection:** If all the previous test meets the defined conditions, a Chi-Squared test is performed to identify a fault in the positioning estimation.
- **Geometry screening:** For each potentially faulty element of the navigation solution, a subset navigation solution is formed by eliminating the faulty element from the all-in-view solution. Then, availability checks are performed to check if the remaining solution would pass, to determine if the detection capability of the solution is sufficient.

Figure 8 and Figure 9 provides a high-level view of the rationale, inputs outputs and relationships of each of the functions detailed.

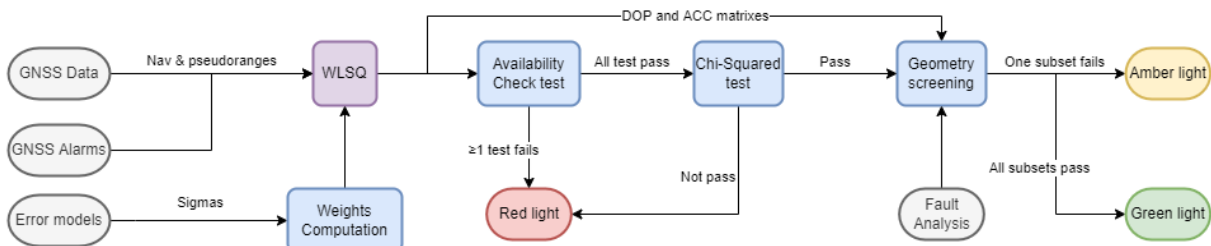


Figure 8 - MGRAIM conceptual flowchart without augmentation

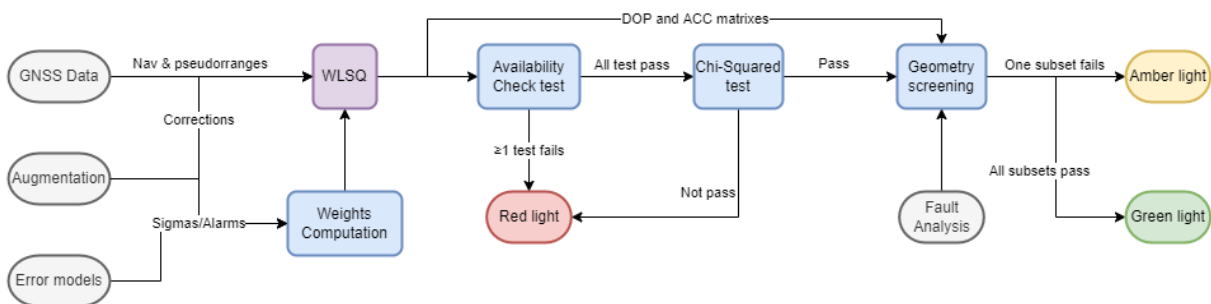


Figure 9 - MGRAIM conceptual flowchart with augmentation

Where:

- Grey bubbles are the required inputs
- Purple box is the PVT engine which computes the user estimated state vector
- Blue boxes are the functions involved in the integrity algorithm
  - Weights computation: computes satellite error models considered as nominal for the maritime environment.
  - Availability Check Test: the function that checks if the current solution is suitable for maritime in terms of expected accuracy.
  - Fault Detection, Chi-Squared test: function that detects if solution complies with the nominal error models.
  - Geometry screening: function that identifies the potential failure and performs additional tests to measurements subsets.
- Red, amber and green light bubbles are integrity warning output information provided to mariners;
  - Red light: provided to the mariner when at least one of the availability check or the fault detection test do not pass.
  - Amber light: provided to the mariner when geometry screening raises an alarm for at least one subset
  - Green light: provided to the mariner when all the tests are performed successfully, and the solution is therefore suitable for navigation.

### 9.1.2.3 High Level DFMC MRAIM Description

The maritime integrity algorithm proposed, is a maritime-specific implementation of the aviation RAIM concept and performs a multiple-hypothesis solution-separation process, then computes a protection level and iteratively optimises this Protection Level (PL) through re-allocation of integrity risk. Solution separation methods are characterised by the use of the distance (separation) between position estimates obtained with subsets of the available satellites.

RAIM is an evolution of the RAIM techniques and has been developed considering DFMC environment with the goal to protect multi-constellation users by means of a robust user

integrity algorithm. Being Civil Aviation applications the driver for the development of ARAIM concept, ARAIM intends to provide a service for stringent aviation operations: LPV-200.

The algorithm is based on the following main principles.

- Ground monitoring system: Different ARAIM concepts might have different levels of ground monitoring and hence would imply different levels of fault detection by the ground segment. This would have a significant impact on the user ARAIM architectures in terms of their performance, and on the design of the algorithm itself.
  - **Horizontal ARAIM** (H-ARAIM) is a minor extension of today's RAIM architecture adding multi-constellation and dual-frequency capabilities. It is based on a static or quasi-static ISD to support horizontal navigation. ISD content is based upon Constellation Service Provider commitments to maintain certain level of performance and observational history.
  - **Offline ARAIM** to support horizontal and vertical navigation based on a monthly ISD from the ground to ensure that ISD parameters are consistent with up-to-date monitoring results. ISD parameters receive greater scrutiny than in the horizontal architecture due to the more stringent operation targets proposed for the offline architecture.
  - **Online ARAIM** to support horizontal and vertical navigation based on an hourly ISD from the ground. In this way, Service Providers are given a larger control over GNSS performance.
- ARAIM assumptions and Feared Events: The ARAIM user algorithm needs to make certain assumptions about errors and threats and requires certain information to be provided by a specific ground segment to generate protection levels and provide integrity. In particular, the user ARAIM algorithm requires values for failure probabilities, the standard deviation of a distribution that bounds the orbit/clock error in the fault-free case and the nominal and maximum biases in fault-free conditions.
- User algorithm:
  - Fault Detection: Each failure mode defines a reduced-subset solution, which excludes the potentially faulty measurements. The physical separation distance between the all-in-view (AIV) solution and the subset solution is used as a fault detection test. Only if all separation tests are passed (i.e., all lie below the detection threshold) is the AIV solution accepted. A conventional chi-square test of the residuals is also performed for the AIV solution as a sanity check.
  - Protection Level calculation: The horizontal protection level is computed that considers all monitored failure modes, nominal errors, and nominal biases. PLs for this algorithm can be computed by two different considerations, MRAIM assuming Rayleigh distribution for horizontal error, or Maritime HRAIM assuming Gaussian distribution for East and North components ignoring the vertical. However, performance are almost identical and therefore same conclusions could be obtained for both, and therefore the assessment will be made only for one of them, the Maritime HRAIM assuming Gaussian distribution.

Figure 10 and **Error! Reference source not found.** provide a high-level view of the rationale, inputs outputs and relationships of each of the functions detailed.

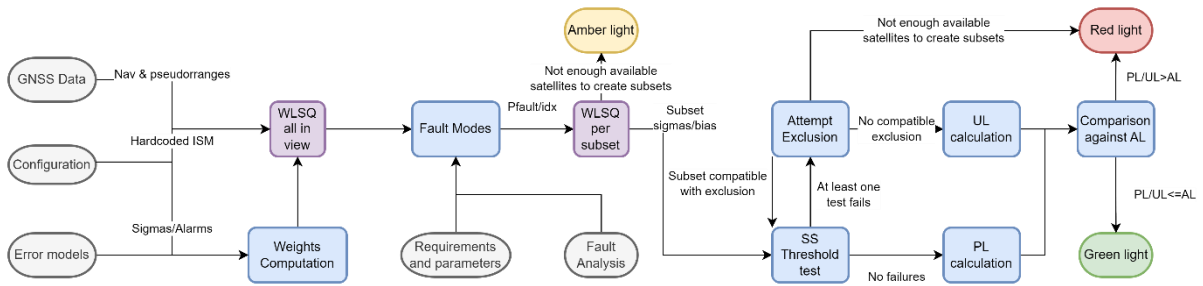


Figure 10 - MRAIM offline conceptual flowchart

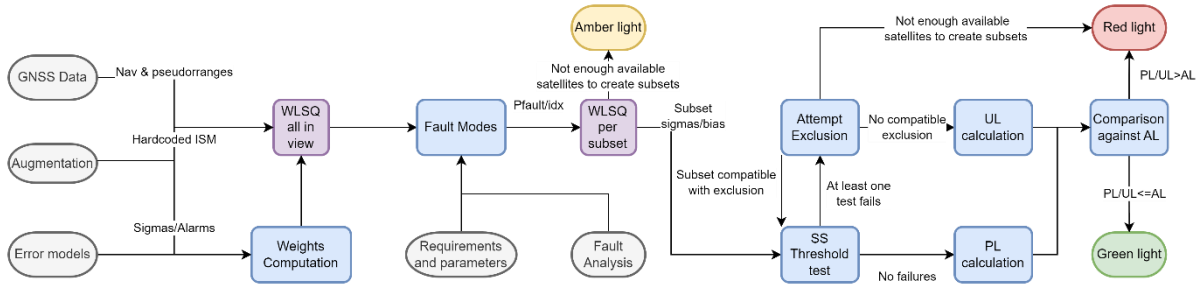


Figure 11 - MRAIM online conceptual flowchart

Where:

- Grey bubbles are the required inputs
  - Particularly relevant are the ISD parameters required for the suitable tuning of the MRAIM algorithm
- Purple box is the PVT engine which computes the user estimated state vector.
- Blue boxes are the functions involved in the integrity algorithm
  - Weights computation: computes satellite error models considered as nominal for the maritime environment.
  - Faults Mode calculation: the function that computes the required subsets to provide the desired level of integrity. According to the fault analysis, this function classifies the error that needs to be monitored to be included in the calculation.
  - Solution Separation Threshold test: the function that performs a threshold test for each subset and analyses if their separation is compatible with a failure. In that case, the faulty could be excluded to provide a safe positioning.
  - Attempt Exclusion: Fault exclusion could be performed if one of the Solution Separation Threshold tests fails. This function computes the compatible potential subsets and provides the compatible subset again to the Solution Separation Threshold test module as the subset is the new “all in view”.
  - Protection/Uncertainty Level calculation: the function that computes the Protection/Uncertainty Level according to the previously computed information.
- Red, amber and green light bubbles are integrity warning output information provided to mariners:
  - Red light: provided to the mariner when the HPL (no fault or fault excluded) or HUL (fault detected and not excluded) is computed and it is above the HAL.
  - Amber light: provided to the mariner when there is not enough satellite available to create subsets and provide a solution for every subset and the integrity requested.
  - Green light: provided to the mariner when the HPL (no fault or fault excluded) or HUL (fault detected and not excluded) is computed and it is below the HAL and no faults are detected.

#### 9.1.2.4 Findings encountered through development and testing

The experimentation conducted has demonstrated the fault detection capability in DFMC scenarios for both MGRAIM and MRAIM algorithms, utilizing DFMC (GPS+GAL) and DFMC+SBAS processing, for a range of real data and simulated faults. These tests validated the algorithm's functionality and compared its fault detection performance between GPS-only and GPS+EGNOS configurations for different types of faults.

The functional testing and performance evaluation were conducted using a collection of real GNSS data (GPS and Galileo observables) gathered from GMV facilities in Nottingham. Comparisons were made to the integrity algorithm developed with EGNOS V3 enabled. To assess the algorithm's ability to detect and, where applicable, exclude faults, simulated data was utilized with faults injected into the RINEX file. This simulated data provided the opportunity to simulate scenarios that could not be realistically reproduced solely using field data.

The results presented for single and multiple satellite faults demonstrate that the algorithm can compute a PVT solution using the MGRAIM and MRAIM concepts. It has been observed that the MGRAIM algorithm is able to detect the fault and raise the appropriate integrity status flag, while the MRAIM algorithm can detect and compute the related HPL.

Following the suitability assessment, further analysis of the integrity algorithm performance was conducted using Monte-Carlo simulations, aimed at evaluating the feasibility of the algorithm performance during each navigation phase. Through these Monte Carlo simulations, further analysis was undertaken to scrutinize algorithm performance and identify the algorithm's strengths and limitations. In these Monte Carlo simulations, further analysis investigates algorithm performance and highlights the advantages and disadvantages of the algorithms.

As with the GPS L1 results from the GPS MGRAIM integrity solution, it should be remembered that these results and conclusions are very dependent on the assumptions used in the generating the data. In particular:

- The fault free performance against requirements is completely dependent on the assumed values for the error models. If it is found that the error models need to be larger or smaller to represent the true errors then this will have a direct impact on the computed values,
- The integrity related parameters (e.g., satellite failure rates) and performance metrics (e.g., HAL) for MRAIM are still somewhat open for the maritime domain. Therefore, the results here – particularly for the solution availability (green status flag) – are very dependent on the chosen parameters and would be different if it is decided in the future that a different HAL, integrity risk, etc. is appropriate,
- The representativeness of the reported metrics, and the fault detection performance, is very dependent on how accurately the error models represent the actual errors. This can be clearly seen in the MGRAIM faulty cases where the reported 95% accuracy is no longer a good estimate of the actual error in the position solution. This means that it is critical that validated error models are defined for use in the actual algorithms on receivers – and for further validation activities.

The final task was to assess the need for a Maritime Specific SBAS Message. The work undertaken aimed to explain the integrity provision of the SBAS maritime system, focusing on expected developments and detailing the current SBAS status to analyse the need for a maritime-specific EGNOS message.

As also concluded within the GPS MGRAIM integrity solution, the proposed integrity algorithm does not necessitate the creation of any new SBAS message or the modification of existing ones. However, this section outlines the anticipated high-level requirements for a maritime-specific SBAS message. Current SBAS messages could be directly employed with a receiver implementation tailored for maritime applications, where certain messages could

be utilized selectively. Additionally, to accommodate varying integrity requirements at the user level, different scale factors could be employed to determine the Protection Level

### **9.1.3 DFMC & DR VAIM integrity solution**

#### 9.1.3.1 Overview

9.1.3.2 INSPIRe also explored, developed, and tested techniques and algorithms for the integration of dual-frequency, multi-constellation GNSS and dead reckoning to establish a vessel autonomous integrity monitoring (VAIM) solution, akin to the well-established aircraft autonomous integrity monitoring (AAIM) concept employed in aviation.

9.1.3.3 This endeavour aims to further enhance user-level integrity and provide additional resilience within the navigation solution. Work on this integrity solution aimed to specifically:

- Generate a clear concept definition for VAIM;
- Conduct an assessment and trade-off analysis of various GNSS and dead reckoning loose coupling schemes to identify the most suitable approach for the maritime environment and requirements, taking into account the potential future need to expand the solution to incorporate other inputs from the resilient PNT system-of-systems;
- Define the VAIM algorithms based on the preferred loose coupling scheme;
- Outline the functional design for the VAIM solution encompassing dual-frequency, multi-constellation GNSS and dead reckoning within a test environment;
- Prototype the algorithms utilizing an appropriate software application (such as MATLAB);
- Execute testing and evaluation of the prototype algorithms within a test environment employing simulated and/or real data, to validate the outline functional design; and
- Assess the feasibility of a maritime VAIM solution, considering both technological challenges and affordability.

The following subsection provides a high-level design for the VAIM algorithm, a description of the development and testing involved, and highlights the benefits and disbenefits of the integrity solution.

#### 9.1.3.4 High Level Algorithm Description

The algorithm is based on three sequential steps once the position is calculated with all the available satellites.

- M(G)RAIM algorithms: Depending on the solution used, the first step is to perform all the procedures considered by the M(G)RAIM integrity concepts, in order to obtain the inputs required for the additional VAIM concept.
- Coherence test: In case an amber or green light is provided by the M(G)RAIM module, it is performed a coherence test comparing the position provided by GNSS and by the dead-reckoning sensors. This positioning is propagated from a previous valid epoch.
- State Vector propagation: In case any of the previous tests provide a non-green flag, the state vector from a previous valid epoch could be propagated, together with its Accuracy of 95% or its PL. This will provide robustness for short failures and outages, and it allows the optimisation of the performance since it could be selected the best solution from the current one and one propagated from a safe previous positioning.

Figure 12 provides a high-level conceptual flowchart of the VAIM modules.

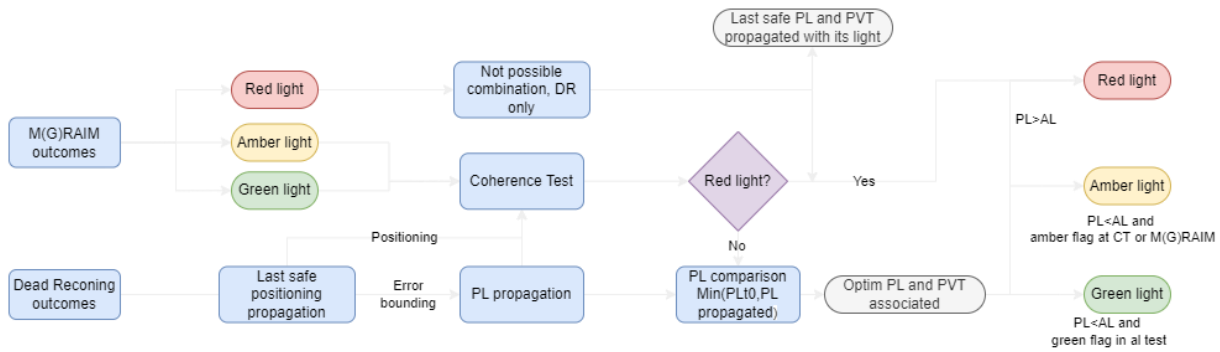


Figure 12 - VAIM conceptual flowchart

Where:

- Grey bubbles are the provided outputs.
- Purple box is a decision point.
- Blue boxes are the functions involved in the integrity algorithm.
- M(G)RAIM: computes GNSS current positioning and integrity alarms.
- Last safe positioning propagation.
- PL propagation: function that identify the potential failure and perform additional test to measurements subsets.
- Coherence Test: function that checks if the current solution is compatible with the information provided by the dead-reckoning sensor.
- Red, amber and green bubbles are output information provided to mariners.

The chart is depicted for a single epoch processing. VAIM algorithm considers the propagation could be made not only from the previous epoch, but for a sliding window. Then, the VAIM algorithm will select those with the best performances (minimum PL or ACC95) and its associated PVT information.

### 9.1.3.5 Positioning estimation before loose couplings

We consider the mathematical process of providing a safe positioning taking into account the information of the positioning and the quality metrics given by GNSS and the other sensor combinations.

From the GNSS M(G)RAIM algorithm the following information will be required:

- Estimated location.
- $A_{95}$  or HPL, depending on the algorithm selected.
- Integrity flag from M(G)RAIM

From non-GNSS device combination the following information will be required:

- Estimated location from the GNSS safe positioning (t-N) epochs ago, where N is a sliding window.
- $A_{95}$  or HPL from the hybridisation technique selected.

This information will allow VAIM algorithm to implement the following two concepts on top of the M(G)RAIM algorithms.

### 9.1.3.6 Development and testing

#### 9.1.3.6.1 Coherence Test

This section aims to detail the coherence test concept. The idea is to compare the two position estimates provided by different sensors to assess whether the information they provide is consistent, or coherent. This may be the first and the simplest integrity concept for hybridisation.

From a general perspective, this concept could be easily understood. When the positioning provided by the GNSS and the positioning provided by the dead reckoning system are too separated, an alarm is raised because one of them (likely the GNSS) is providing misleading information.

The issue is then to evaluate what is considered as “too separated” and to define a threshold. An appropriate characterisation of devices nature selected would allow the usage of statistical tools such as hypothesis contrasts, which can be configured for different levels of confidence and therefore an integrity risk can be derived.

The principle consists of calculating both the position solution and evaluating the difference between them. If the bias between them is big enough this test will alarm to avoid using the position solution. On the other case the probability that this error is not detected will be lower than a value PMD (Probability of Miss Detection).

In addition to that, with the typical accuracy of the second sensor and the IR/PMD it will be defined the necessary bias for a faulty case to fulfil that requirement. Therefore, it will be provided a MDB (Minimum Detectable Bias) on real time about what is the smallest error could be detected with that IR/PMD. This is the indeed a limitation in the bias detection capability, errors smaller than MDB cannot be detected with the requested probability, and they may cause integrity breaks.

If this test is made propagating the position only from the last GNSS positioning, only step errors could be detected. Therefore, it is proposed to perform this test iteratively propagating the positioning from the last N epochs to the current one, in order to detect also potential ramp errors.

Taking this concept into consideration, the following integrity flag concept is proposed:

- In case any alarm is raised (positioning difference over the threshold), the overall positioning will be flagged as red and no safe positioning will be provided.
- In case no alarm is raised (positioning difference below the threshold), but the largest MDB is larger than the required accuracy, an amber flag will be raised.
- A green flag will be raised when no alarm is detected (positioning difference below the threshold) and the largest MDB is smaller than the required accuracy.

#### 9.1.3.6.2 GNSS state vector propagation

The second concept for a GNSS loose coupling with other sensor, not exclusive from the previous one, is the capability to propagate previous GNSS safe positioning and provide an error bounding, in a similar way as ACC95 and PL do.

The position of the GNSS solution selected in the previous epoch is propagated employing the measurements received from the alternative sensors since the previous safe epoch considering the status now when the solution was generated.

Then, the positioning accuracy (ACC95) or the positioning bounding (PL) of the M(G)RAIM solution selected in the previous epoch is increased to ensure that the PL considers and bounds the position propagation errors. The amount in which these parameters will have to be increased will depend on the time passed from the moment when the previous selected solution was generated, on the quality of the sensors and on the initial errors.

In order to compute this additional bounding of the error propagation, to be added to the ACC95 or the PL, the following steps shall be performed.

- Compute the overbounding of the velocity errors, at each  $\Delta t$  propagation step based on the sensor error overbounding parameters.
- Based on the overbounding of the velocity errors, the user velocity and the overbounding of the initial heading error, compute the heading angle error bound after  $k$  propagation steps corresponding to the TIR

- Based on the overbounding of the velocity errors, the user velocity and the overbounding of the heading, obtain the increment of PL for the corresponding TIR or the propagation of the ACC95 due to the propagation of k steps

The vessel can pass in a short period of time from open-sky or good visibility conditions to harsh conditions (e.g., in port navigation), in such situation the previous propagated ACC95/PL can be lower than the one computed at that epoch. The objective of proposed approach is to try to reduce the impact on the availability caused by such conditions and maximise the performances.

This optimisation of the performance is then done selecting the smallest ACC95/PL from all the valid ones from the sliding window propagated to the current epoch. Then, the estimated location is the one associated to that minimum ACC95/PL.

If this test is made propagating the position only from the last GNSS positioning, only step errors could be detected. Therefore, it is proposed to perform this test iteratively propagating the positioning from the last N epochs to the current one, in order to detect also potential ramp errors.

Taking this concept into consideration, the following integrity flag concept for each epoch is proposed:

- A red light will be raised:
  - In case any alarm is raised by M(G)RAIM, or the coherence test if used before this algorithm.
  - The overall ACC95 or PL is larger than the defined threshold.
- Amber flag will be raised if an amber flag is raised by the M(G)RAIM, or the coherence test if used before this algorithm.
- A green flag will be raised when no alarm is detected and the propagated ACC95 or PL remains under the configured threshold for the navigation phase.
- In case that for the given epoch a red or amber flag is raised, the sliding window allows the user to provide the last safe positioning propagated to the given epoch.

### 9.1.3.7 Summary

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

*Table 2 - Summary of VAIM integrity algorithm output states per epoch*

M(G)RAIM	Coherence test	PL from M(G)RAIM	PL propagated	PL selected	Status Flag	PL and position from
	N/A	N/A	PL Propagated from previous green flag epoch	Min(PL propagate from green flag epoch)	RED	From purely propagation from green flag epoch
	RED	PL M(G)RAIM	PL Propagated from previous green flag epoch	Min(PL propagate from green flag epoch)	RED	From purely propagation from green flag epoch
	AMBER/ GREEN	PL M(G)RAIM	PL Propagated with epoch information and from previous green flag epoch	Min(PL M(G)RAIM ; PL Propagated) > AL	RED	From M(G)RAIM or propagated

M(G)RAIM	Coherence test	PL from M(G)RAIM	PL propagated	PL selected	Status Flag	PL and position from
	AMBER/ GREEN	PL M(G)RAIM	PL Propagated with epoch information and from previous green flag epoch	Min(PL M(G)RAIM ; PL Propagated) ≤ AL	AMBER	From M(G)RAIM or propagated
	AMBER	PL M(G)RAIM	PL Propagated with epoch information and from previous green flag epoch	Min(PL M(G)RAIM ; PL Propagated) ≤ AL	AMBER	From M(G)RAIM or propagated
	GREEN	PL M(G)RAIM	PL Propagated with epoch information and from previous green flag epoch	Min(PL M(G)RAIM ; PL Propagated) ≤ AL	GREEN	From M(G)RAIM or propagated

### 9.1.3.8 Benefits and disbenefits of the solution

The experimentation focused on Vessel Autonomous Integrity Monitoring. This is a maritime-specific implementation of the M(G)RAIM concepts developed in this project to provide the requested integrity including dead-reckoning techniques, similar to aircraft autonomous integrity monitoring (AAIM) concept used in aviation, enhancing user-level integrity and providing additional resilience in the navigation solution.

Functional testing and performance evaluation were conducted based on the collection of real GNSS data (GPS and Galileo observables) in the fjord at Trondheim, Norway. Comparisons were made to the integrity algorithm developed with EGNOS GPS L1 enabled. To evaluate the VAIM algorithm's ability to use information from non-GNSS sensors to perform a consistency check on the positioning domain, and to perform a safe propagation technique of the last GNSS estimated epoch and its positioning accuracy of 95% (ACC95) or PL in case of GNSS outage or significant performance degradation to improve performance on top of detecting and, where applicable, excluding faults. Simulated data was used with faults injected into the RINEX file. The simulated data provided an option to cover scenarios that would otherwise not be possible using field data alone.

The results presented are for faults applied on single and multiple satellites and have shown that the algorithm is able to compute a PVT solution using the MGRAIM and MRAIM concepts with VAIM enables. It has been observed that the MGRAIM algorithm is able to detect the fault and raise the appropriate integrity status flag. While the MRAIM algorithm can detect and compute the related HPL.

The VAIM algorithm is technically feasible, as it can improve the performance of M(G)RAIM algorithms that only use GNSS. This concept follows the IMO's approach for multi-system shipborne receivers, where positioning and integrity information from different sensors are fused to provide more robust, accurate, and safer positioning.

The proposed algorithm is developed for a combination of a speed sensor and compass. However, the high-level idea is technology-agnostic and could be easily adapted to any other sensor onboard a SOLAS vessel or expanded to use more than one dead reckoning sensor

simultaneously. It would only be necessary to modify the propagation equations. For example, IMUs or laser sensors could be considered for further VAIM developments.

It is also important to note that VAIM is an algorithm that works on top of M(G)RAIM, so its overall performance depends on the GNSS algorithm selected. VAIM smooths out performance, backs up GNSS in case of loss of availability, and provides an additional integrity check. However, it only propagates the previous GNSS ACC95/PL. Therefore, performance compliance must be evaluated with both M(G)RAIM algorithms.

For navigation phases where VAIM performance is not sufficient, different GNSS solutions should be explored until the accuracy and PL are within the expected range. Then, better dead reckoning sensors could improve the stability and availability of the navigation solution.

However, VAIM requires safe characterization of dead reckoning errors. INSPIRe has considered an error model to generate synthetic data, but the safety of the concept in a real application depends on the characterization of the error. This will be a key technical activity for operational VAIM development.

Regarding operational considerations, VAIM implementation in SOLAS vessels should be easy and quick. There are no regulatory barriers. In fact, VAIM is aligned with the aforementioned IMO regulations and could already be implemented for the dead reckoning sensors that are already mandatory. The only complexity could be the implementation of a centralized element where information from GNSS and dead reckoning sensors is provided and fused.

The cost of implementation is limited to the new central element if it does not already exist on the vessel. Otherwise, the cost is negligible since the sensors used in VAIM are already mandatory and do not require additional processing capabilities. Every element is already on board, and only the vessel's software would require an upgrade. Vessels already have sensors that allow them to navigate in each phase, so it is not expected that any additional sensors or costs will be required.

However, the penetration of this technology typically takes a long time, as mariners only change their equipment when required to do so or when they see a clear advantage. The need for integrity in maritime is still under question, so a slow rate of navigation equipment upgrade is expected.

## **9.2 Prototype RAIM Availability Prediction Tool**

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INSPIRe has developed a prototype availability prediction tool which enable the user to identify the expected integrity performance of their position solution based on location.

### **9.2.1 Overview**

INSPIRe aimed to design, develop and produce the prototype RAIM availability prediction tool, similar to, but extended from, the EUROCONTROL AUGUR facility. This tool models the availability of RAIM for combinations of GNSS frequencies and constellations considering the RAIM algorithms developed in INSPIRe. The tool predicts RAIM availability across the UK to the limits of the EEZ and further as time and effort permit.

The following sub-sections provide an overview of this tool and its design, the required processing to be performed by the tool, and summarises the outcomes from developing the tools.

### **9.2.2 High level M(G)RAIM Performance Prediction Prototype Tool Design**

This section provides a general overview of M(G)RAIM Performance Prediction Prototype Tool design. The prototype tool is based on the following main modules:

- **User Location & Satellite visibility:** These two modules take as input the desired user location (single point or a grid of users) and the GNSS constellation almanac to compute the relative constellation geometry.
- **Error model computation:** This module considers the background GNSS error models to compute the weight matrix. In addition, the GNSS health status is considered in order to exclude flagged satellites. This GNSS health status considers the NANUs/NAGUs messages and could include messages from augmentation systems.
- **M(G)RAIM module:** This module computes the M(G)RAIM performances, Accuracy, PL and alarms, for the configured scenario.
- **Performance Statistics:** To provide to the user with the required statistics, this module takes the M(G)RAIM performances and process them as required.
- **Monitoring System (Optional):** Finally, this additional module could monitor the real performances and compare it against the forecasted ones, to fine tuning and refine the used error models.

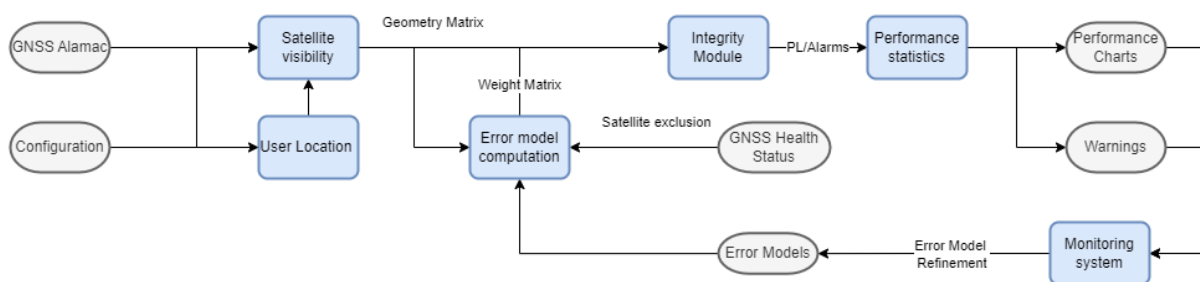


Figure 13 - M(G)RAIM Performance Prediction prototype tool

### 9.2.3 Inputs

M(G)RAIM Performance Prediction Prototype Tool requires the following inputs:

- **Configuration:** The tool considers the following configuration parameters:
  - User location / User grid definition
  - Date and expected time window
  - Constellation(s) to be used
  - Satellites to be used
  - M(G)RAIM configuration parameters
  - Navigation phase requirements
- **GNSS almanac:** Tool requires the closest available GNSS constellation ephemeris to the user configured date. These ephemeris in an operational tool should be obtained from a network of receivers decoding real data. However, in this prototype the almanac will be obtained from a navigation RINEX file or a plain text file with the satellite orbital information.
- **GNSS Health Status:** The operational tool should take as input the NANUs, NAGUs or equivalent messages that provide information about the GNSS constellation and satellite health status. In addition, it should take into account as inputs augmentation system information, if used, about GNSS health information.
- **Error models:** Finally, a signal error model for each constellation and frequency is provided to the M(G)RAIM Performance Prediction Prototype Tool. These models in the operational tool could be provided by a user configuration or taken from augmentation system signal error estimations. In addition, the M(G)RAIM monitoring system could compare the forecast against the real performances and refine the models. In the prototype tool this function will be performed manually tuning the error models introduced by configuration.

## 9.2.4 Processing

From a functional perspective, the M(G)RAIM Performance Prediction Tool should perform the following high-level processing. Please note that processing described applies equally to an operational tool and also to the prototype.

### 9.2.4.1 User Location & Satellite visibility

These two modules together take as input the desired user location (single point or a grid of users) and the GNSS constellation almanac to compute the relative constellation geometry.

Inputs:

- User location / User grid definition: From configuration it is required to input the user location, or the parameters that defines the user grid unambiguously. This location is usually given by coordinates of a user or the parameters that define the grid coordinates.
- Date and expected time window: From configuration it is required to input the desired date and for how many hours the forecast is needed. Please, note that the combination of the date and the time window cannot exceed 72h from 00:00 UTC of the current date.
- Constellation to be used: From configuration it shall be selected which constellation to be used.
- Satellites to be used: From configuration, it shall be selected if any satellite is excluded by any reason prior to the health checks.
- GNSS almanac: Orbital parameters of configured constellation are required to estimate satellite location for the desired time interval.

**Processing;** the input information should be handled according to the following steps:

- Satellite orbital information is decoded and satellite position, of every satellite configured, is propagated to every epoch configured. Satellite position shall be computed in an Earth Centred Earth Fixed (ECEF) reference frame. The following steps shall be performed per user configured or per epoch if a dynamic single user is configured:
  - User location is converted from coordinates (latitude, longitude, height) into an ECEF XYZ vector.
  - Rotation matrix ECEF $\leftrightarrow$ ENU/NED reference is computed for the user location.

The following steps shall be performed per user and per epoch configured:

- The relative satellite position from the user's point of view is computed in the ECEF reference frame and then converted into ENU/NED.
- Satellite azimuth and elevation are then computed, and elevation mask exclusion is applied to identify visible satellites.

Outputs:

- One elevation and azimuth angle per line of sight, user and epoch configured.

### 9.2.4.2 Error model computation

This module considers the background GNSS error models and GNSS health status in order to compute the weight matrix.

Inputs:

- Satellite relative positioning: For the configuration, it is required to input the user location, or the parameters that define the user grid unambiguously. This location is usually given by the coordinates of a user or the parameters that define the grid coordinates.

- Configured Error models: Preliminary background models should be configured in order to provide the required information to the M(G)RAIM algorithm even if no external information is provided. These models need to be conservative to over-bound the error since they are used for integrity purposes, for a wide variety of environments.
- Refined Error Models: Feedback information about current real performances could be considered if augmentation systems or any other kind of monitoring system is deployed. These refined models will be prioritised on top of the configured ones since they are expected to better fit the real performances.
- GNSS Health Status: GNSS status information such as NANUs, NAGUs or equivalent messages shall be considered as inputs, together with information broadcast by the GNSS core constellation and also the augmentation system, if used. This integrity information will be used to exclude faulty satellites from the forecast computation.

**Processing:** the input information should be handled according to the following steps:

- The following steps shall be performed per user and per epoch configured:
- Configured Error models are applied to each visible satellite measurement, depending usually on satellite elevation. Then one model is obtained per line of sight. These models will be different for each GNSS constellation or combination of measurements.
- Feedback information, if available, will be decoded and a satellite measurement model will be obtained, depending on the GNSS constellation or combination of measurements. The refined error model obtained for each satellite will then overwrite the one obtained from the configured model.
- GNSS Health status information shall be decoded and healthy flags should be obtained for the visible satellites. If the satellite is flagged as unhealthy for any reason, the weight of that satellite should be set equal to 0.

Outputs:

- One variance per line of sight, per user and epoch configured.

#### 9.2.4.3 Integrity Module

This module computes the M(G)RAIM performances, PL, and alarms, for the configured scenario.

Inputs:

- Satellite location: From the previous module, one elevation and azimuth angle per line of sight, per user and epoch is required.
- Variance: From the previous module, one variance per line of sight, per user and epoch is required.
- Configuration parameters:
- M(G)RAIM configuration parameters should be provided, including first of all the algorithm selection (MRAIM or MGRAIM) and all specific parameters required for the algorithm computation.
- Navigation phase requirements: Navigation requirements are required to set some key parameters required for the algorithm computation.

**Processing:** the input information should be handled according to the following steps:

- MRAIM or MGRAIM processing is performed according to the detailed information contained in the technical reports.

Outputs:

- Warnings/Alarms: The tool provides warnings to those users when the expected performances are not suitable for the configured navigation phase.
- Protection Level: Protection Level size performance is provided for the selected configuration.
- Accuracy Level: An estimate of the 95% fault-free Accuracy performance is also provided.

#### 9.2.4.4 Performance Statistic

In order to provide the required statistics, this module takes the M(G)RAIM performances and processes them as required.

Inputs:

- Warnings/Alarms: Alarms per user and epoch are taken to be processed.
- Protection Level: Protection Level size per user and epoch are taken to be processed.
- Accuracy and DOP values: per user per epoch
- Configuration parameters:
  - Navigation phase requirements: Navigation requirements are required to provide performance statistics again the given threshold.
  - User location / User grid definition: User location is required to plot the statistics in a chart or a map.
  - Date and expected time window: A date and time window is required to plot results for the configured time.

**Processing:** the input information should be handled according to the following steps:

- MRAIM or MGRAIM outcomes should be plotted in a figure along time for a given user.
- MRAIM or MGRAIM outcomes statistics (percentiles, availability, etc.) should be computed according to the configuration.

Outputs:

- Warnings/Alarms: Devoted messages in text format and figures when the expected performances are not suitable for the configured navigation phase.
- Protection Level: Protection Level size charts and/or maps for the selected configuration.

#### 9.2.4.5 Monitoring System

This additional module could monitor the real performances and compare it against the forecasted ones, in order to fine tune and refine the used error models.

Inputs:

- Warnings/Alarms: Alarms per user and epoch are taken to be analysed.
- Protection Level: Protection Level size per user and epoch are taken to be analysed.
- Real performances: Monitoring system collects information from real data in order to be processed according to the algorithm selected.

**Processing:** the input information should be handled according to the following steps:

- MRAIM or MGRAIM Performance Prediction forecast are compared against the real performances for a given user on a given time window. If performances are too optimistic or pessimistic, actions should be performed in order to tune error models.

Outputs:

- Refined error models: Updated error models obtained after correction actions.

### 9.2.5 Outputs

Finally, the M(G)RAIM Performance Prediction Prototype Tool provides the following outputs:

Performance charts:

- The tool, in a single user mode, provides the following information along the time window:
  - Satellite visibility information
  - Expected service outages (due to poor performances or signal unavailability)
  - PL size (if appropriate)
  - Expected 95% Accuracy performance
- The tool, in a user grid mode, provides the following information along the time window:
  - Availability maps
  - PL size maps
  - Accuracy maps
- Please note that an operational tool may provide this information via a web interface or a devoted report in, for example, pdf format. However, these charts are provided by the prototype tool in as independent images.

**Warnings/Alarms:** The tool raises warnings to those users when the expected performances are not suitable for the configured navigation phase. These alarms in the operational tool may be provided via web interface or a devoted text message. In the operational tool it will be provided as images for the user or selected area.

**Other outputs:** Finally, the tool also provides the output information in plain text mode.

### **9.2.6 Outcomes**

The experimentation conducted demonstrates functionality of the Performance Prediction Prototype Tool. It has been observed that the tool is able to provide for the 24h and 72 selected where applicable the following information:

- Satellite visibility information
- Availability maps
- Expected service outages.
- Protection Level size
- Foreseen alarms
- Warnings to those users when the expected performances are not suitable.
- Output information in plain text mode
- A forecast excluding satellite from NANUs, NAGUs or equivalent
- A forecast considering different frequencies of usage

The work carried out also included steps and timescales for the development and implementation of an operational tool. As a recommendation the roadmap for the development of an operational M(G)RAIM Performance Prediction tool will be developed in two stages:

Building on the performance and functionality tested within the work package, a roadmap was developed and out of this which proposes a two-stage development plan for an operational M(G)RAIM Performance Prediction tool. These stages include activities to:

- 1) Upgrade the prototype tool developed in this project to a functional, online, service that anyone can access. Its purpose would be mainly educational, to raise awareness of integrity at sea, and to inform today's mariners of the capability that their receiver is likely to provide.
- 2) Develop the Provision Scheme for an operational prediction service, along with the IALA / IMO process to get changes made to maritime equipment. This second stage will consider the final implementation of the M(G)RAIM algorithms if they are finally incorporated into maritime receivers.

Additionally, a series of the main actions have been identified to implement an operational Performance Prediction Tool from the prototype already developed. These activities are:

- Incorporation of M(G)RAIM proposed solution
- Service provision analysis
- Prediction Tool core processing development
- Development of Performance Prediction Tool interfaces
- Deployment of monitoring network stations (Optional)
- Performance Prediction Tool Test Bed
- Maritime user engagement

The expected development roadmap is detailed in the following figure.

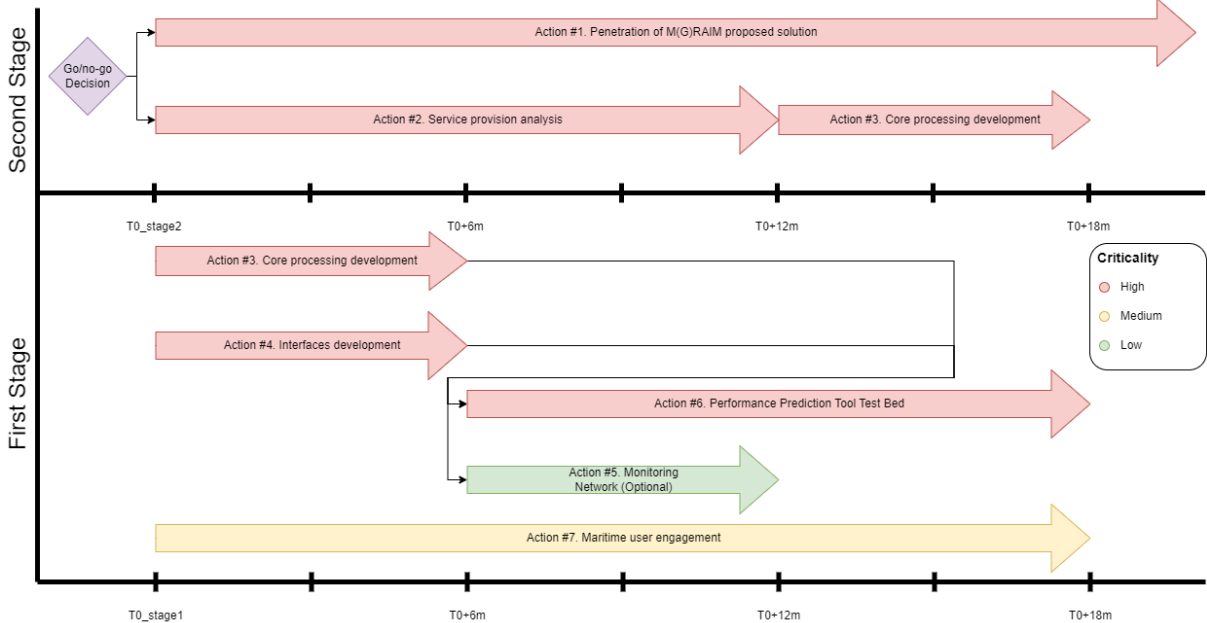


Figure 14 - Operational Performance Prediction Tool Roadmap

Actions have been classified by their criticality, indicating the relationship among the actions and the expected timeframe.

## 10 SYSTEM LEVEL INTEGRITY CONCEPTS

### 10.1 Prototype EGNOS Monitoring Solution

#### 10.1.1.1 Introduction and Purpose

Following the UK's exit from the European Union, and subsequent exit from the Galileo and EGNOS programmes, the UK finds itself without any domestically controlled GNSS infrastructure. This is a concern both for UK industry, but also national security and defence. Solutions are being considered to address the security concerns of finding ourselves outside the fence with regard to the EU's two main GNSS programmes, in particular a solution to the UK military no longer having access to secure, authenticated Galileo signals.

A more immediate threat is the loss of EGNOS-guided approach procedures for UK airports. EGNOS provides significant value for the aviation sector by allowing smaller airports to offer EGNOS-guided precision and non-precision approaches, meaning fewer landing aids and less ground infrastructure is required at the airport. Since Brexit, the UK is no longer covered by the EGNOS safety-of-life service, and all EGNOS-based approaches to UK airports have been removed.

INSPIRe aimed to investigate the feasibility of monitoring the EGNOS system for the purpose of providing an integrity guarantee, such that EGNOS safety-of-life services can be re-established in the UK. The integrity monitoring that maritime users of the system would require, looking both at today's needs and a potential future maritime safety-of-life service was also considered.

#### 10.1.1.2 Approach

The approach taken was to analyse the functionality of the EGNOS system, to break down the process into a hierarchy of technologies, both physical (monitor stations and hardware), virtual (software and data processing), and political (legal instruments and institutional guarantees).

On a purely engineering level, no material changes have been made to the EGNOS system. The system works as well in the UK as it ever has, and will continue to do so as long as its use in neighbouring EU nations is supported by the bloc. Indeed, there is no physical way in which the EGNOS system could continue to function in the local vicinity of the UK (particularly in the Republic of Ireland) while, at the same time, not functioning in the UK.

The only aspect of EGNOS functionality that has been removed is the legal framework, including service level agreements and liability guarantees, previously extended by the EU to support safety-of-life use by civilian aviation in the UK.

#### 10.1.1.3 Technical Solution

In the absence of a definitive set of monitoring requirements for the UK, the work package described potential monitoring requirements that would depend, quite critically, on the level of implicit trust extended to the EGNOS system. Just as EGNOS was described in terms of a hierarchy of technologies, the institutional trust that UK authorities place in the system depends entirely on which layer of that technology hierarchy is trusted to function correctly.

Some simple examples are given:

- If the base technological hardware is not trusted to function, including the delivery of the SBAS data stream to the UK (and this could include deliberate service denial) then the trust placed in EGNOS is zero. A UK system would have to replicate all aspects of the system, including monitor stations, processing centres and duplicate GEO satellites and data delivery pathways.
- If the basic space hardware is trusted to function, but the SBAS integrity service is not, then the UK system need not replicate large parts of EGNOS, but could simply verify the integrity of the service that EGNOS delivers. The UK user would then access the EGNOS

system as before, but would also need a real-time alerting system, such that the UK monitor could call a halt to operations if the service was found to be at fault. Monitoring EGNOS integrity would likely require a network of equivalent density and geographical distribution to the current EGNOS RIMS network.

- The mathematical argument is put that it is not possible for the EU to safely extend an integrity guarantee to its citizens without, at the same time, also extending the same guarantee over UK airspace. Broadcast integrity parameters that are valid within the EGNOS footprint are, by definition, also valid in the UK as we are wholly contained within that footprint. If the UK government could accept such an argument, then the monitoring requirements could be considerably lessened, merely to verifying that the EGNOS system is functional, and that no catastrophic failure has occurred.
- The ultimate trust of the EGNOS system would be to offer institutional liability guarantee without monitoring the system at all. For as long as the EU supports its use in Europe, the system will continue to function correctly in the UK. This may not be a palatable option in the current political climate.

A simple monitor is proposed to verify that EGNOS is functional, and that no catastrophic failure of service has occurred. A monitor closely related to the WAAS User Position Monitor (UPM) was chosen, as this monitor is the one trusted by the FAA, and it is also described extensively in the open literature.

Coupled to this proposed monitor is a system to collect and archive EGNOS broadcast data, for the purposes of replicating service area diagrams and prediction services akin to the EU's own availability prediction services such as the AUGUR tool. An EGNOS service area prediction tool was developed taking real historical EGNOS data and extrapolating the extent of the system's service footprint over the UK. A variety of different user performance requirement thresholds can be configured, such that service areas for different user segments can be produced, including aviation NPA, LPV and maritime integrity services. M-RAIM and MG-RAIM algorithms can be configured, and the software computes the availability of the user-level integrity service accordingly.

#### 10.1.1.4 Outcomes

The simulations have indicated that the current EGNOS (V2) offers a comparatively poor integrity service for the mariner, although this is linked to the assumed local noise and multipath environment on the ship, and is consistent with simulated results from WP2 and WP3.

#### 10.1.1.5 Conclusion

It is concluded that EGNOS based approaches could be re-established in the UK provided a suitable governmental, or quasi-governmental liable entity could be established. This entity would then need to accept responsibility for the proper functioning of EGNOS in the UK, and would need to extend the same legal and financial liability guarantees to UK aviation, previously offered by the EU.

The requirements for UK monitoring of EGNOS would then be dictated directly by the due-diligence concerns of that entity. Since this liable entity does not exist, and there exist no plans to create such an entity within government, there exist no current requirements to monitor EGNOS in the UK. Indeed, it was observed that the UK's decision to establish its own SBAS service testbed can be interpreted as an intention to remain separate from EGNOS, at least for the foreseeable future.

## 10.2 DFMC Integrity Monitoring (DIM) Service

The DFMC Integrity Monitoring (DIM) Service is proposed to provide system level integrity assurance for maritime DFMC users in the UK European 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 DIM Service is constructed as an integrity service only. In particular, no augmentation of the GNSS navigation information will be generated or available to users.

Figure 15 presents a high-level DIM System conceptual architecture.

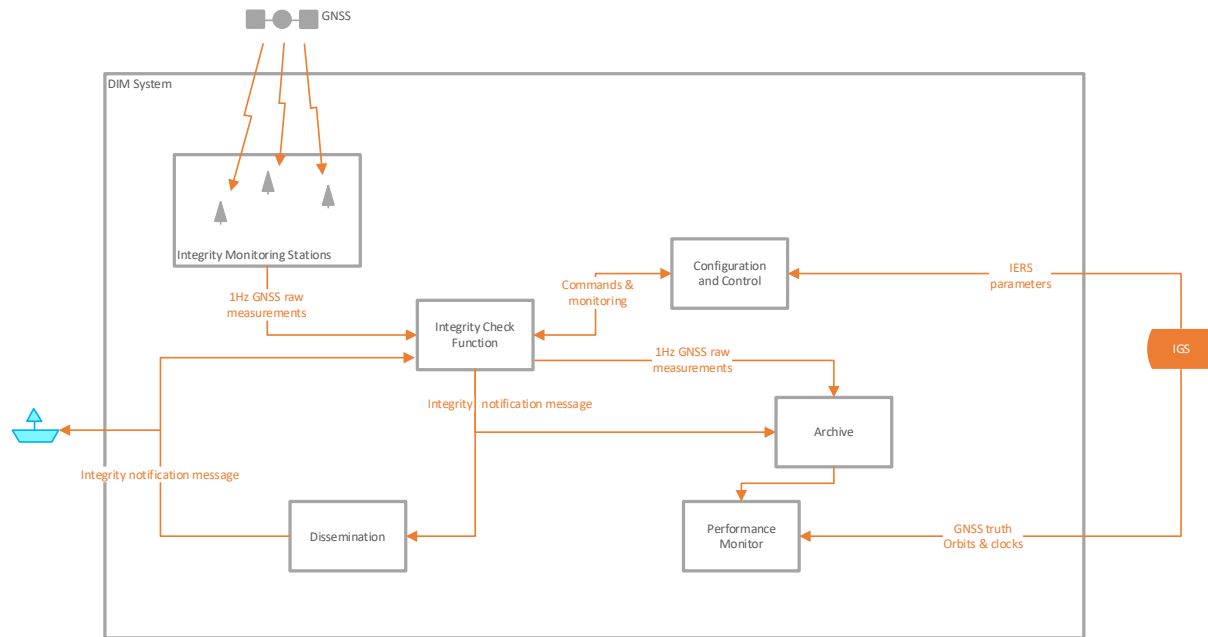


Figure 15 - DIM System Conceptual Architecture

Seven Integrity Monitoring Stations, evenly distributed across the UK land mass, 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.

The Integrity Check Function assesses the integrity of the monitored GNSS satellites based on the measurements taken by the Integrity Monitoring Stations and constructs a single Integrity Notification Message each second to the Dissemination Function for onward distribution to the users of the DIM Service.

The Dissemination function facilitates the dissemination of the Integrity Notification Message to the users. A variety of dissemination technologies will be employed under the umbrella of an e-Navigation Service on the Maritime Connectivity Platform (MCP).

As a provider of integrity assurance, the DIM Service requires safety certification. Accordingly, the DIM System will be developed to commensurate stringent development assurance levels. The full safety analysis of the system has not yet been completed but will allocate final development assurance levels to all system components and will establish appropriate barriers against hazards.

The DIM Service provides users with an assurance of integrity of the GNSS navigation data, in particular satellite ephemeris and clock information. 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 key performance indicators for the Service are extremely stringent false alarm probability constraints and availability requirements.

### ***10.2.1 Development and testing of the system***

A Proof of Concept Testbed implemented a suite of algorithmic candidates and conducted experimentation with real UK based observations of GPS and Galileo satellites, as well as specially injected feared events.

The objective of the DIM System is to assure integrity throughout the UK EEZ relying exclusively on UK based assets. The narrow observation base results in geometric dilution because all line-of-sight vectors will be almost parallel in East-West direction. As little as 1% of an error may be observable from UK shore-based assets if the error is orthogonal to these lines of sight. This constraint renders algorithms unfeasible which attempt to model the full 4-dimensional ephemeris error.

Unlike SBAS, the performance of an integrity monitoring system crucially depends on the performance of the monitored GNSS constellations. For an SBAS, the probability of false alarm can for example, be improved through improved position/clock corrections or inflated error bounds. An integrity monitoring system has no control over the actual GNSS error distributions and therefore the occurrence of borderline alarms. False alarm and missed detection probabilities depend on the performance margins provided by the monitored GNSS constellation. The DIM service cannot quantify its performance without reference to those GNSS constellation performances.

For the same reason, the DIM integrity cannot build or publish an error bound bottom up, as in the WAAS approach, but will perform a final integrity test. In line with several other SBAS systems, this test will consider the measurement sample variance in its decision threshold.

The Proof of Concept Testbed demonstrates the critical importance of raw measurement quality. Many barriers, such as barriers against cycle slip or multipath, will not operate effectively if the underlying measurement noise exceeds certain levels, resulting in significant performance degradations. The study concludes that a DIM Service would not be able to utilise existing UK stations but would be required to deploy and maintain their own dedicated stations. An alternative approach, using a far greater number of lesser stations, was outside the scope of the study.

The study identified a concern regarding how user receivers manage the inter-system clock offsets between constellations. To our knowledge, receiver behaviour is not standardised in this regard so that misinterpretation of DIM integrity assurances remains a significant risk. 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 positioning errors which were not monitored or considered by the DIM algorithms.

The Proof of Concept Testbed's false alarm performance does not meet requirements, primarily due to the low quality of available raw measurements. Therefore, additional experimentation and simulation will be required with raw measurements consistently meeting the quality specified for monitoring stations. We also highlight that the INSPIRe false alarm requirement applies to the user's (M)RAIM solution and is not directly applicable at DIM system level: Whilst a DIM system level false alarm on a single satellite reduces satellite availability, it leads to a user level (M)RAIM false alarm only in combination with significant other contributors. The classic definition of false alarm does not consider this user impact probability.

At the time of PoC Testbed experimentation, the GPS L1-L5 constellation had not reached critical mass to support an L1-L5 dual frequency service so that GPS dual frequency

performance could not be determined. For a DIM Service, the GPS constellation will need to have reached critical mass, which is expected by around 2027.

The study assessed two means of dissemination to mariners. Maritime Safety Information as part of the Global Maritime Distress and Safety System is not appropriate for the distribution of regular (1Hz) Integrity Notification Messages and as it is reserved for infrequent human-readable navigation warnings. e-Navigation services will need to employ a combination of VHF, mobile or satellite communication technologies in order to meet the Service needs for all geographies and phases.

### ***10.2.2 Benefits and relevance of the DIM Service***

The key benefit of DIM Service to a user operating a DFMC (M)RAIM algorithm, is that 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.

The DIM Service provides integrity assurance, but not augmentation. Therefore, it will not be able to use the existing single frequency, nor future dual frequency standard of navigation SBAS interfaces. Instead, an additional standard will need to be developed and adopted to enable equipment manufacturers to develop user receivers capable of processing the DIM Service messages, and ensure that user receivers interpret the DIM integrity assurance information correctly at all times when computing protection levels. The buy-in of worldwide competent authorities and equipment manufacturers cannot be guaranteed at this stage, especially for a service only available in UK European EEZ.

The restriction to utilise only UK based monitoring stations constrains the availability of the service. Users, especially those furthest away from UK shores, will have visibility of satellites up to 20 minutes before the central system will be able to confirm their monitored status. In that sense, the DIM Service may reduce, rather than enhance the capabilities of users' (M)RAIM. Furthermore, the DIM Service is, by design, unable to generate warnings relating to the user's local environment such as scintillation which may represent the most significant source of error to the user.

All functions of the analysed DIM Service would naturally also be provided by any future DFMC SBAS Service over the UK, which could render the DIM Service redundant.

### ***10.2.3 How the DIM Service contributes towards a maritime integrity architecture***

The DIM Service is designed to support users of dual frequency multi-constellation GNSS navigation through the UK European EEZ, as part of a System of Systems. It allows users to combine the benefits of dual frequency navigation with those of an independent integrity assurance. This combination is not currently available.

The DIM Service provides a traffic light status for each GNSS satellite and is intended to be consumed by the user's DFMC GNSS receiver. The traffic light status is not intended for direct human consumption. User receivers must implement a dedicated standard of algorithmic processing to ensure that the DIM Service information is correctly interpreted.

The DIM Service increases the robustness and integrity of the user receiver's (M)RAIM by warning about faulty satellites. As an integrity monitoring system, the DIM Service has no augmentation function and will therefore not enhance the positioning solution accuracy in the fault free case, which remains the responsibility of the (M)RAIM algorithm.

### **10.3 Opportunistic sources of data to aid DFMC integrity**

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#### **10.3.1 Summary of the integrity solution developed**

INSPIRe has assessed the feasibility of augmenting dual-frequency multi-constellation GNSS integrity monitoring using crowd-sourced integrity data from users. The work focused on the maritime sector, considering potential expansion into other sectors where integrity is a key performance metric in critical applications.

Firstly the feasibility of incorporating crowdsourced user integrity data into the UK-wide dual-frequency, multi-constellation GNSS integrity monitoring system, considering different approaches and taking account of potential drawbacks was evaluated. The scope of review covered an extensive range of PNT technologies, including but not limited to, signal-of-opportunity sources (such as indoor positioning technologies, shore-based AIS, and eLoran), CORS networks, computer vision techniques, and utilising information from nearby vessels. The feasibility assessment culminates in identifying two high-priority approaches for INSPIRe: system-level crowdsourcing and user-level crowdsourced positioning.

#### **10.3.2 Findings encountered through development and testing**

##### **10.3.2.1 System-level crowdsourcing**

The system-level crowdsourcing approach utilised CORS network as an opportunistic data source to support system-level integrity monitoring. This includes enhancing error characterisation which can highly improve the system performance. The developed integrity monitoring algorithms in INSPIRe currently assume that measurement errors follow a Gaussian distribution. As this is not always the case, there's a trade-off affecting system safety and availability, emphasizing the need for better error characterisation in mission-critical applications. The significance of this approach lies in the fact that the overbounding process for a Gaussian assumption can account for over half of the protection level region. In other words, overbounding the Gaussian distribution to ensure safety often results in an overbound that doubles the computed protection level without overbounding, underscoring the importance of replacing the Gaussian assumption with a distribution that characterises the data more accurately.

In this approach, we developed an error characterisation framework using Gaussian, Generalized-t, GEV, Logistic, Laplace, and Cauchy distributions. These distributions were evaluated based on three main criteria:

- fit (overall and tail),
- impact on system availability,
- and bounding, while considering computational complexity.
  - The assessments used for these evaluations include the Kolmogorov-Smirnov (KS) test, graphical assessment, and availability assessment. The KS test assesses the distribution's overall fit, while the graphical assessment evaluates fit (both tail and core) and overbounding. The availability assessment determines the impact on system availability.

##### **10.3.2.2 User-level crowdsourcing**

User-level crowd-sourced positioning has been developed based on using nearby vessel information to enhance the positioning and integrity algorithms in the maritime sector. This is especially relevant because the current GNSS cannot provide the required level of performance, particularly at the port. Furthermore, the proposed user crowd-sourced

positioning concept can also be expanded to include other sectors where integrity is a critical performance metric.

The fundamental concept of crowd-sourced positioning is based on leveraging nearby vessel positioning and integrity information, which can be transmitted via the Automatic Identification System (AIS). In addition, it also encompasses range measurements that can be computed using Radar and/or Lidar technology.

In simpler terms, this layer contributes to system safety by establishing connections between all nearby vessel positions, moving beyond the traditional approach of solely linking vessel positions with satellites, as shown in Figure 16. Furthermore, user-level crowd-sourced positioning can enhance the system's situational awareness due to its foundation in relative positioning modes, and this layer can be extended to include tracking and predicting the locations of nearby vessels. In addition, the adaptive relative positioning utilised in this layer provides a basis for further developments of anti-spoofing and anti-jamming techniques, ensuring a more secure and reliable system.

This approach is introduced as an additional layer to the two-integrity monitoring layers in INSPIRe. In real-time operation, the system level integrity sends to the user the required integrity information to ensure safe operation. Then at the user-level, the GNSS devices receive this information to compute the position and protection level. The proposed layer then is based on transferring positioning information between the vessels to compute the protection level within a third layer. Figure 17 presents the functional architecture of these three layers.

**10.3.3 Key benefits and disbenefits**

**10.3.3.1 System level crowdsourcing**

The results indicate the potential benefit of an adaptive error characterisation approach, dynamically selecting one of four distributions (Gaussian, GEV, Logistic, and Laplace) based on real-time quality indicators. In scenarios lacking an adaptive method, the Logistic distribution is recommended, with considerations for overbounding.

**10.3.3.2 User level crowdsourcing**

User-level crowd-sourced positioning can enhance the system's situational awareness due to its foundation in relative positioning modes, and this layer can be extended to include tracking and predicting the locations of nearby vessels. In addition, the adaptive relative positioning utilised in this layer provides a basis for further developments of anti-spoofing and anti-jamming techniques, ensuring a more secure and reliable system. This approach is introduced as an additional layer to the two-integrity monitoring layers in INSPIRe.

The effectiveness of this model was demonstrated using a simulator from Imperial College, designed to handle various configuration parameters like the number of nearby vessels, geometry, and range sensors. The results show the potential of this approach to significantly enhance navigation system performance, particularly when employing high-accuracy LiDAR for measuring distances between vessels.

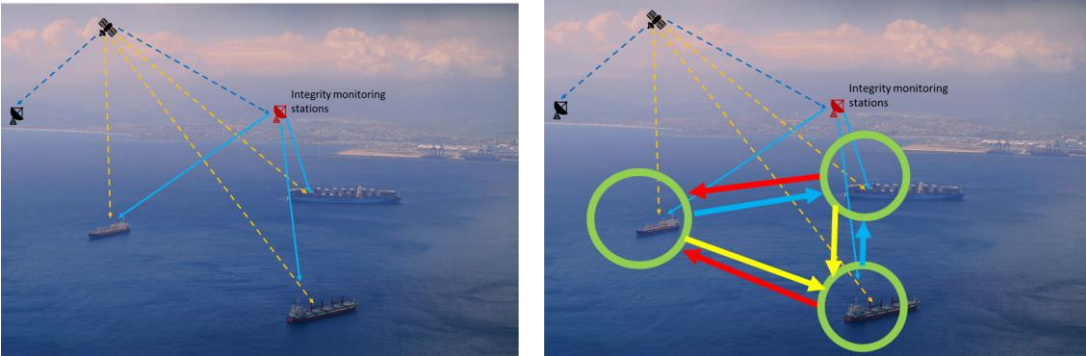


Figure 16 - Traditional approach of linking vessel positions to satellites vs contribution of crowd-sourced positioning

The left side illustrates the traditional approach of linking vessel positions to satellites, while the right side demonstrates the contribution of crowd-sourced positioning in establishing connections between the positions of all nearby vessels in addition to satellite.

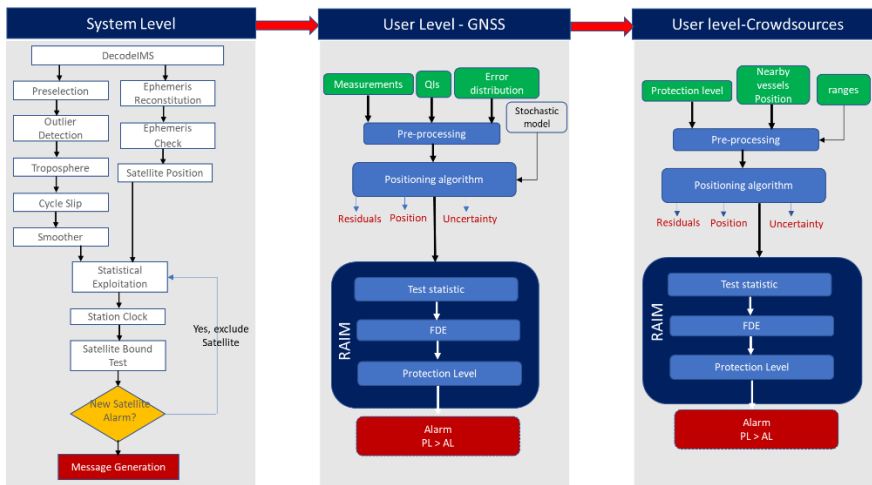


Figure 17 - Functional architecture

Figure 17 presents the functional architecture of these three layers, the system level architecture developed within WP8.

## 11 IMPLEMENTATION AND EXPLOITATION PLANNING

This section of the report defines the implementation and exploitation roadmap to implement these integrity concepts as an integrity architecture and identifies opportunities to exploit them in the maritime sector.

### 11.1 Maturity of the user-level integrity concepts

#### 11.1.1 Current level of Maturity

The current maturity of the integrity concepts is estimated by the project by using the European Space Agency (ESA) definitions of Technology Readiness Level.

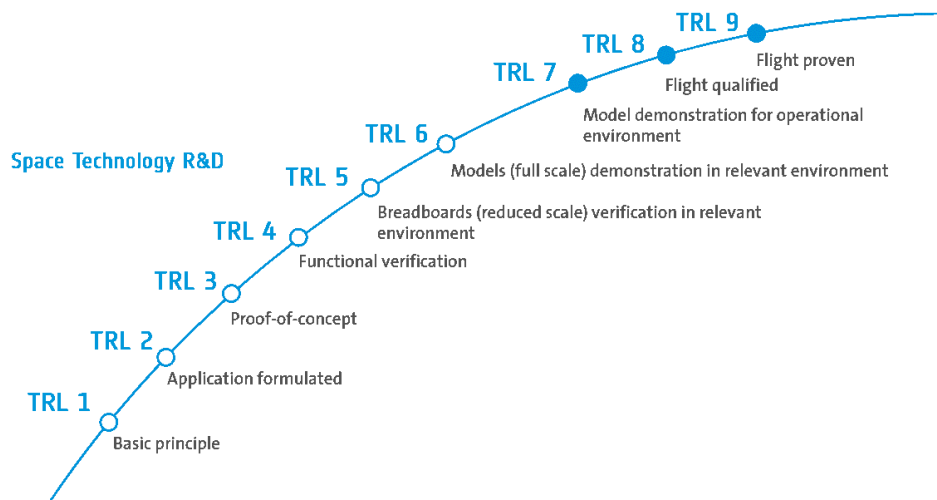


Figure 18 - European Space agency TRLs. Source: ESA

Table 3 summarises of the maturity of each concept and provides the estimated TRL. Further discussion of the maturity of each of the integrity concepts is provided in D1.1.

Table 3 - Technology Readiness Levels of integrity concepts developed in INSPIRe

Integrity Concept	TRL achieved in INSPIRe	Summary of maturity
User-Level		
MG-RAIM	4	Software test-bed implementation subject to functional validation with injected integrity faults
M-RAIM	4	Software test-bed implementation subject to functional validation with injected integrity faults
VAIM	3/4	Software test-bed proof of concept for using DR data to support integrity monitoring
Opportunistic Sources (Ship-to-ship integrity monitoring)	2/3	Early concept demonstration using simulated vessel positions and ranging data
System-Level		
UK DFMC Integrity Monitor	3/4	Software test-bed implementation subject to functional validation with injected integrity faults

Integrity Concept	TRL achieved in INSPIRe	Summary of maturity
UK EGNOS Monitor	2/3	Proposed method for implementing a monitoring system based on existing WAAS implementation
Opportunistic Sources (Error characterisation)	3	Early concept of alternative error characterisation methods, which aims to improve system-level DFMC integrity monitoring
Supporting Tools		
RAIM Performance Prediction Tool	4/5	Prototype software tool hosted on a local environment

### 11.1.2 Performance of the user-level concepts

Each of the integrity concepts has been evaluated against INSPIRe's requirement set to assess the functionality, performance and integrability of each concept.

Section 10 contains a summary of the validation results and D1.1 discusses the V&V results for each integrity concept in further detail.

The detection capabilities and performance achieved by the user-level algorithms are summarised in D10.1 The performance results were evaluated for various configurations of GNSS receiver, including GPS L1, DFMC, and with SBAS augmentation.

#### 11.1.2.1 MG-RAIM and M-RAIM

The MG-RAIM and M-RAIM user-level algorithms are shown to successfully detect ramp and bias errors and provide an integrity alert, both in the case of single satellite and multiple satellite faults.

Performance results demonstrate that up to Coastal Phase performance band can be achieved using GNSS inputs based on the accuracy, availability and continuity requirements.

It should be noted that the validation is based on simulated errors, and thus further validation is required to assess the integrity performance of the algorithms within the context of a maritime environment.

#### 11.1.2.2 VAIM

VAIM is shown to successfully detect ramp and bias errors when the DR navigation system is integrated with the MG-RAIM and M-RAIM algorithms. This demonstrates the potential to integrate alternative positioning inputs as an additional integrity monitoring layer to GNSS to improve integrity monitoring performance.

No performance validation of the VAIM algorithm has been completed, due to the complexity of the relationship between GNSS and DR information inputs. Further study will be required to assess the performance benefit of VAIM.

#### 11.1.2.3 Peer-to-peer communication

The peer-to-peer communication integrity concept has been functionally demonstrated as improving the confidence and thus integrity of the positioning solution.

The integrity concept was not sufficiently mature to enable validation against the INSPIRe requirement set however the functional validation does demonstrate potential of peer-to-peer communication methods in improving integrity performance.

### **11.1.3 System-level integrity concepts**

The system-level integrity concepts were evaluated against the requirement set to identify how the system-level solutions can support the user.

#### **11.1.3.1 DFMC Integrity Monitor**

DIM is shown to successfully detect single satellite and multiple satellite errors and generate an integrity flags. This demonstrates the potential of the DIM to generate a DIM message which may be disseminated to users.

The performance benefit of the DIM to the user will require user-level processing to be developed and dissemination methods to be implemented to enable the DIM message to benefit to the user.

#### **11.1.3.2 EGNOS Monitor**

The EGNOS Monitor proposes a User Position Monitoring (UPM) algorithm based on the WAAS augmentation network to monitor EGNOS outputs. This has been subject to validation as part of the WAAS implementation thus no further performance validation of the EGNOS monitor has been conducted within this project.

#### **11.1.3.3 RAIM Prediction Tool**

The RAIM Prediction Tool is shown to successfully predict the service availability and performance of a user's MG-RAIM and/or M-RAIM algorithms. The validation results demonstrate the ability of the tool to produce a performance prediction which aligns with the expected performance of the MG-RAIM and M-RAIM algorithms.

The notion of GNSS threat detection is not relevant to the RAIM Prediction Tool, as the tool is a prediction tool which cannot detect threats. The activities required to implement the RAIM Prediction Tool are detailed in D10.1.

### **11.1.4 Maturing the user-level concepts**

There are eight key activities identified and recommended in order to advance the advance the TRL of the user level algorithms to operational maturity, these are listed below but further details can be found in D10.1.

- Characterising local fault conditions in the maritime environment:

Local error models are key to characterising navigation performance of GNSS in the maritime environment, to consider the effects of NLOS and multipath errors when establishing a position. However, for the maritime sector local error modelling remains a significant challenge due to the complexities and varied nature of the local environment, where errors may be induced due to the quality and placement of receiver installations, reflections from the ground, and obstruction from port infrastructure and other vessels.

It is recommended that there are further long-term trials across multiple vessels to improve knowledge of local error models in the maritime environment and thus improve the integrity performance of user-level algorithms.

- Integrating VAIM with other DR sensors:

VAIM provides a concept to integrate DR sensors and other navigation inputs with GNSS information to provide integrity monitoring. In INSPIRe VAIM has demonstrated integration of GNSS integrity algorithms with speed and compass based DR sensors.

The concept is also designed to be expanded by integrating more complex DR sensors such as INS and IMU sensors which are already mandated for many SOLAS vessels.

Further expansion of VAIM and testing will be required across multiple vessels and DR sensors to manage differences between vessels and DR sensor outputs.

- Integrating peer-topper methods with user-level receivers:

Integration of LiDAR data with peer-to-peer data has been investigated as a signal of opportunity at proof of concept stage to further improve the user level integrity performance to user-level ship-borne equipment. The results presented within D8.1 have shown significant potential of this concept in high-traffic environments where multiple positioning results can be compared, also with ranging information from LiDAR to increase the certainty of the position result.

- Technical advancements of the user-level algorithms:

Within D8.1 a number of future development opportunities are identified to further improve the integrity performance of the user-level. These present opportunities for further research and development incorporating improved error characterisations through deploying non-Gaussian distributions. The key opportunities are identified here and further explored within D8.1:

- developing a user-level adaptive error characterisation framework at the measurement domain;
- developing a user-level adaptive error characterisation framework at the position domain; and
- developing a Machine Learning-based protection level prediction model.

- Integrating the DIM message with user-level receivers:

The DIM, as currently developed within INSPIRe, provides a proof-of-concept test bed which can provide an integrity message to users to support improved integrity performance.

To identify and evaluate the benefits of the DIM for the user, user-level processing of the DIM message needs to be developed and tested. Further development of the DIM should also evaluate the potential for wider adoption of DIMs outside of the UK EEZ. A wider adoption of DIMs will provide a stronger case for adoption and standardisation of DIM messages at the user-level and spread the costs associated with development and assurance of the DIM system.

- Performance validation of user-level algorithms in the maritime environment:

Within INSPIRe, the user-level algorithms are evaluated within a software test bed environment. This environment simulates faults by injecting faulty scenarios within fault-free GNSS receiver data. This provides a functional and performance baseline for the algorithms but does not necessarily reflect real-world conditions, which are likely unpredictable with multiple compounded errors.

In order to fully evaluate the user-level algorithms, it is therefore critical to understand their performance in a real-world maritime environment. D10.1 suggests a number of further validation activities.

- Peer review and validation of the integrity concepts:

INSPIRe's integrity concepts have been subject to technical review and validation by the project's consortium throughout the project. This has enabled both technical and operational PNT experience in maritime and other sectors to be considered within the development of the integrity concepts.

D10.1 provides a summary of the activities taken to review the user-level and system-level integrity concepts.

Further peer review of the integrity concepts from external stakeholders is strongly encouraged throughout future development and validation.

- Developing user-level test standards:

To enable widespread adoption of the user-level receiver algorithms by receiver manufacturers, a suitable and robust suite of test standards needs to be developed for various grades of maritime receiver, building on the current IEC standards. This will enable a consistent level of integrity performance of the GNSS positioning solution to be achieved across vessels.

## **11.2 How INSPIRe's integrity concepts can support standards**

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Currently in the maritime sector, the IMO is the organisation responsible for international navigation performance and regulation. Standards are implemented internationally recognising that vessels need to be interoperable across international waters.

INSPIRe has recognised several key areas in the extant maritime standards which need to be developed to promote a widespread adoption of integrity, which have been explored in previous studies are noted in D10.1. There is currently an inconsistent adoption of GNSS performance and integrity across the maritime sector at the user-level, depending on the constellation used. This results in variable levels of safety and variable dependence on GNSS navigation performance between vessels and fleets.

The results from INSPIRe can be used at a high level to support the development of maritime standards. This could be achieved through using the results to define a consistent and standardised level of GNSS performance to be met across the regulated maritime sector with clearly attributed requirements for user-level and system-level, as an enabler for improved safety and future use cases.

INSPIRe's user-level integrity concepts demonstrate user-level receiver algorithms which provide a means of meeting the GNSS performance requirements and improving the integrity performance of GNSS based navigation and positioning, using concepts which are suitable for the maritime sector.

INSPIRe's system-level integrity concepts demonstrate approaches that could be taken forward nationally to support maritime users. These concepts include the DIM, EGNOS Monitoring and the RAIM Prediction Tool.

INSPIRe provides the baseline and algorithms that can form the basis for the development of standards.

Refer to D10.1 for further details.

## **11.3 Recommendations for developing the maritime standards**

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INSPIRe has developed four recommendations for developing the maritime standards.

These are:

1. User requirements for a ship's navigation system need to be developed and formalised to provide a set of navigation performance requirements which are suitable for all current and future navigation use cases in maritime.
2. GNSS receiver performance, functional and testing standards need to be further developed to consider achievable performance requirements for GNSS, considering both the user requirements but also receiver citing requirements, local multipath and NLOS error characterisation. These considerations need to be applied within standardised testing methods to ensure consistent grading of receivers to enable a standardised level of navigation performance to be attributed to a vessel's GNSS information.
3. MG-RAIM, M-RAIM and VAIM concepts present opportunities for developing internationally recognised integrity approaches for maritime for achieving GNSS navigation performance, to enable a consistent approach to achieving the relevant performance requirements to be defined within relevant navigation standards.

4. National infrastructure needs to be led by the UK Government and supported by functional and interface standards to enable effective user level adoption. For maximum interoperability of national systems these standards need to be implemented and supported internationally.

## **11.4 Implementing the system-level and supporting integrity concepts**

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### ***11.4.1 Implementing the RAIM performance Prediction Tool***

The RAIM Performance Prediction tool is configured based on the M(G)RAIM algorithm in use (MG-RAIM or M-RAIM), appropriate error models and the required navigation performance bands, as described in Section 11.

The tool has two modes of operation:

- Single User mode provides a prediction of the user's integrity status over a given time frame (e.g. 24 hours), and
- User Grid mode provides a prediction of the integrity status for a given area over a given time frame.

The development of the Performance Prediction tool will be undertaken in two stages, this will involve:

- Upgrading the prototype tool developed in this project to a functional, online, service that anyone can access. Its purpose would be mainly educational, to raise awareness of integrity at sea, and to inform today's mariners of the capability that their receiver is likely to provide.
- Developing the Provision Scheme for an operational prediction service, along with the IALA / IMO process to get changes made to maritime equipment. This second stage will take into account the final implementation of the M(G)RAIM and MRAIM algorithms to be incorporated into users' receivers.

In order to implement an operation Performance Prediction Tool there are seven activities to be completed. These are:

Action 1 – Adoption of the user-level algorithms

Action 2 – Analyse the service provision for the tool, involve stakeholders and assess the liabilities and interface among them

Action 3 – RAIM Prediction Tool core processing development to upgrade the current prototype into a functioning tool

Action 4 – Development of RAIM Prediction Tool interfaces to comply with high-level requirements

Action 5 - Deployment of monitoring network stations to compare real performances against forecasted performances, this would help to fine tune and refine error models (Optional)

Action 6 – Develop a RAIM Performance Prediction Tool Test Bed to test functioning of the tool prior to operation

Action 7 – Promote the tool to maritime users through engagement

The actions above will support successful implementation and exploitation of the RAIM performance prediction tool however its adoption is largely dependent on whether the M(G)RAIM algorithms are also adopted.

### **11.4.2 Implementing the EGNOS Monitor**

The EGNOS monitor implementation roadmap focuses on the activities required to implement a monitor which will enable the UK to re-instate the aviation SoL services LPV-200 and APV-I for aircraft approach and landing procedures.

The implementation roadmap then proposes that service requirements outside of aviation, for example maritime, can then be developed and later supported.

There are two key technical components in the UK EGNOS Monitor:

- A UK based monitoring network implementing a UPM to independently identify the service status of EGNOS V2 and EGNOS V3 services to enable Safety of Life Guarantee; and
- An EGNOS Availability Tool which monitors the service coverage of EGNOS satellites which are monitored by the UK monitoring network, and therefore the area of which a Safety of Life guarantee can be made to users by the UK EGNOS Monitor

The following components need to be delivered for the implementation of the EGNOS monitor within maritime:

- Six monitor sites, requiring a control server, and three EGNOS receivers (primary, backup and standby), and associated hardware such as cabling, cabinets, power, data communications, etc.
- Two control centres, consisting of server machines hosted at secure locations, with a workstation to access the system, and public-facing web access to interface to the coverage software, and access the EGNOS data stream as a digital service akin to the EGNOS Data Access Service (EDAS). The public facing web access will most likely be hosted remotely.
- A full deployable version of the GMV coverage tool.
- A suite of monitor and control software to handle data processing at the monitors, health status monitoring, secure data communications, including remote access to the monitor sites.

The time frame for implementation of the EGNOS monitoring system must allow for a sufficient period of time post-INSPIRe to gain support for commissioning the system, time to establish a regulatory framework for a UK government liable entity to be established, allowance for the tendering process and then installation of the system, periods for both the Initial Operating Capability and Final Operating Capability to be tested and establishment of cross-sector applications.

This time frame suggests that within three years of the end of INSPIRe EGNOS SoL approaches for UK airports can be re-established.

### **11.4.3 Implementing the DFMC Integrity Monitor**

The DFMC Integrity Monitoring (DIM) service provides a proposal for a land based integrity monitoring concept using UK based integrity monitoring stations.

The integrity monitoring stations are highly validated GNSS receivers which provide input data to a centralised control centre and output an integrity notification message. The message provides users with integrity information for the satellites in view of the DIM's monitoring stations.

The message is either shared via MSI as a human readable Integrity Warning Message or via e-Navigation services as an Integrity Support Message providing the live integrity status.

The DIM service requires several key functions to be implemented:

- DFMC Integrity Monitoring Stations
- Central Configuration and Processing Facility

- Dissemination Service (MSI and/or e-Navigation)
- A Competent Authority, responsible for the Institutional Framework required to support the DIM

#### 11.4.3.1 Prior to DIM service Implementation

Implementation of the DIM service is based on a number of dependencies:

- The GPS constellation is scheduled to reach 24 operational satellites broadcasting L5 estimated in around 2027; this level of capability is required for the DIM.
- All competent authorities, relating to standards, communications and to qualification and certification must be identified and engaged to ensure the DIM Service development meets all governance requirements.
- The achievable algorithmic modelling performance, the selected sites, and the selected technology must be finalised to inform the safety analysis and assurance levels of the DIM. This will result in a comprehensive allocation of performance, safety margins and development assurance levels to the system components which will enable detailed development plans and component designs.
- A period of prototyping is required to mature the design of the DIM and its components such that it can meet the required assurance level of such as system.
- The complexities of the local maritime environment need to be further understood based on the use of the DIM service. The DIM Service development plan therefore includes a period of three years between system completion and start of safety-of-life operations.

Prior to implementation of the DIM service, there are a number of technological and environmental research topics which will need to be understood, these include:

- Receiver, Antenna and Clock Hardware
- Site Surveys
- Algorithmic Enhancements
- Proof of performance

Another step to overcome before implementation of the DIM service is that any maritime SoL service must be governed by a comprehensive institutional framework. As the DIM service provides integrity assurance but not augmentation, it is unable to use the existing standard of navigation SBAS broadcasts, and therefore a future phase of INSPIRe must define and adopt an alternative standard through engagement with a competent authority. Once adopting this standard, the DIM Service must be certified by a certification authority.

#### 11.4.3.2 Dissemination of the DIM service

There are two potential paths for dissemination of the DIM service:

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

##### Dissemination via MSI

The idea 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 and the entirety of the DIM service sits within NAVRAREA-I.

A working agreement to determine roles and responsibilities, wording of the MSI, frequency of alerts and expectation as to how rapidly alerts can be disseminated to the mariner must be established between the DIM systems operator and the Admiralty. 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.

Once established, a communication channel would be opened for the DIM System operators to send integrity alerts to the Admiralty, which will then be sent to the maritime users.

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 via e-Navigation

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.

#### 11.4.3.3 Dissemination Implementation Plan

Two implementation paths will have to be followed for the DIM service.

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 is dependent on the Admiralty's receptiveness to disseminating the output from the DIM network to the mariner, the speed with which a working arrangement can be agreed and the necessary time needed between the DIM System becoming established and the commencement of the MSI integrity warnings. Significant attention will also need to be given to understanding the accuracy of the integrity alerts and the issue of false alerting.

The second path followed will be of dissemination via the MCP as an e-Navigation service. This is far out of the control of INSPIRe due to much of the MCP infrastructure currently not being established as an operational system and still being in development, which is going to take several years to be completed. The data communications infrastructure necessary to disseminate the integrity messages to the ships would need to be established and standardised and the timeline for delivery is uncertain.

#### ***11.4.4 Further development opportunities at the system-level***

Further to the DIM Service developed in D7.1 further investigation has been undertaken within D8.1 to investigate methods of improving the system-level performance through improved error characterisation.

The study investigated five alternative error distributions compared to the standard gaussian distribution utilised for charactering errors; being the Generalised-t, GEV, Logistic, Laplace and Cauchy distributions.

The results demonstrated opportunity to provide improved availability of the DIM Service through better characterisation of errors whilst maintaining integrity risk performance, with a potential for adaptive error characterisation to be applied in real time based on understanding of quality indicators and other factors.

D10.1 proposes four further activities to improve the performance of and thus implement these alternative error characterisations. These are:

- Develop a robust adaptive error characterisation framework capable of selecting the error distribution based on real-time quality indicators using Machine Learning.
- Devise a mechanism that simplifies the utilisation of the GEV distribution, which has shown the best results in terms of mapping extreme events. This can improve the system performance including accuracy, integrity, availability, and continuity.
- Integrate the Logistic distribution into the existing DIM system, applying overbounding techniques to guarantee the system's safety.

- Investigate the error characterisation for carrier phase measurements error, to support high accuracy carrier-phase integrity monitoring in the future.

## **11.5 Maritime Exploitation opportunities**

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The regulated maritime sector is the principal target market for the INSPIRe concepts, that is vessels that operate internationally and fall under the SOLAS convention. Vessels that do not operate internationally but are involved in safety, operationally, environmentally or economically critical activities and are regulated as such on a national basis will also form part of the target market.

### **11.5.1 MG-RAIM, M-RAIM and VAIM**

These user-level integrity concepts are applicable to applications that need high levels of integrity in real-time, particularly when system-level integrity is not available or not sufficient to take local factors into account. RAIM is already present in most maritime GNSS receivers but is not standardised and does not have performance requirements. There is a market opportunity for a standardised maritime RAIM solution of proven performance, especially in the light of the cessation of the IALA DGNS service and lack of coverage or acceptability of SBAS solutions (both of which only provide system-level integrity in any case).

It is likely the main application for these integrity concepts will be general navigation for both crewed and autonomous vessels.

The general navigation applications are typically:

- In the ocean phase where other sources of integrity are not available
- In the coastal phase again where other sources of integrity are not available
- On the port approach, entrance and port phase where system-level integrity solutions may not be adequate to account for local conditions, such as multipath.

The European Union Space Programme Agency (EUSPA) has completed extensive requirements capture for many maritime applications. In addition to general navigation, maritime use cases that would likely benefit from user level integrity include (but are not limited to):

- Sea traffic management
- Inland waterway navigation
- Fisheries
- Oceanography
- Dredging
- Marine Engineering
- Cable laying
- Aids to Navigation management;
- Traffic management
- Operations: automatic collision avoidance and track control.
- Search and Rescue: final rescue approach; and
- Offshore exploration and exploitation

### **11.5.2 DFMC Integrity Monitoring**

This is a system-level integrity monitoring concept that monitors the integrity of the satellites in view using a UK based monitoring network to provide an integrity status of GNSS satellites, which can be used to disseminate integrity information to directly to users or through Notices to Mariners (NtMs).

System-level DFMC integrity monitoring would likely be a useful supplement/facilitator of RAIM solutions but would require a system and associated standards for distribution of data. This could be achieved through AIS/VDES.

### **11.5.3 A UK EGNOS Monitor**

This is a system-level integrity monitoring concept which monitors the outputs of EGNOS to provide means for a UK liable entity to assure a Safety of Life guarantee for EGNOS augmentation data within the UK exclusive economic zone (EEZ). This concept includes an availability tool which monitors the availability and coverage of the area assured by the EGNOS monitor. This would only likely be a stop-gap solution addressing liability issues to enable users to benefit from EGNOS until a UK SBAS becomes available.

### **11.5.4 Peer-to-peer data sharing (crowd-sourcing)**

Crowdsourcing can be categorised into user-level and system-level types and has potential to support a wide range of mission-critical applications including aviation, maritime, autonomous vehicles, robotics, precision agriculture, and autonomous drone operations

For applications where integrity requirements are met (e.g., aviation), system-level crowdsourcing will reduce the alarm limit requirements in future, which can enhance operations. For applications where requirements are not currently met, such as autonomous vehicles, robotics, and precision agriculture, system-level crowdsourcing can be a key element in achieving necessary performance levels in the future.

### **11.5.5 Supporting tools**

The RAIM Performance Prediction Tool investigated by INSPIRe is a software tool that forecasts the integrity performance for a user and has potential to be a useful tool in strategic and tactical voyage planning, where the market will be for the service likely provided from a single, central entity perhaps as part of a NtMs. However, the deployment of the RAIM prediction tool is dependent on the adoption of MG-RAIM and M-RAIM.

## **11.6 Opportunities arising from the emerging UK policy framework**

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UK government has recently released its policy framework for greater resilience in PNT. This framework is predicated on the statement “*strengthening PNT capabilities, will give direction to the [UK] PNT industry, while fostering innovation, growth, and cutting-edge technology development, positioning the UK as a global PNT leader.*”

The new framework provides three key exploitation opportunities for INSPIRe. These are:

- INSPIRe concepts can access other sectors where they may find application due to the central focal point provided from the framework where PNT cross-sector needs and opportunities can be consolidated and addressed.
- Through the PNT growth policy, particularly relating to its development, standardisation and testing components to provide impetus for the INSPIRe concepts to overcome the R&I valley of death between TRLs four and seven
- By promoting the rollout of resilient GNSS receiver chips (assumed to comprise hardware, middleware and software in this context) where embedded RAIM algorithms may be an integral part of resilience. MG-RAIM and M-RAIM are good foundations on which to build validated and standardised RAIM solutions for the maritime sector with scope for adaptation and extension to other sectors.

## 11.7 Getting to market

### 11.7.1 Overcoming the valley of death

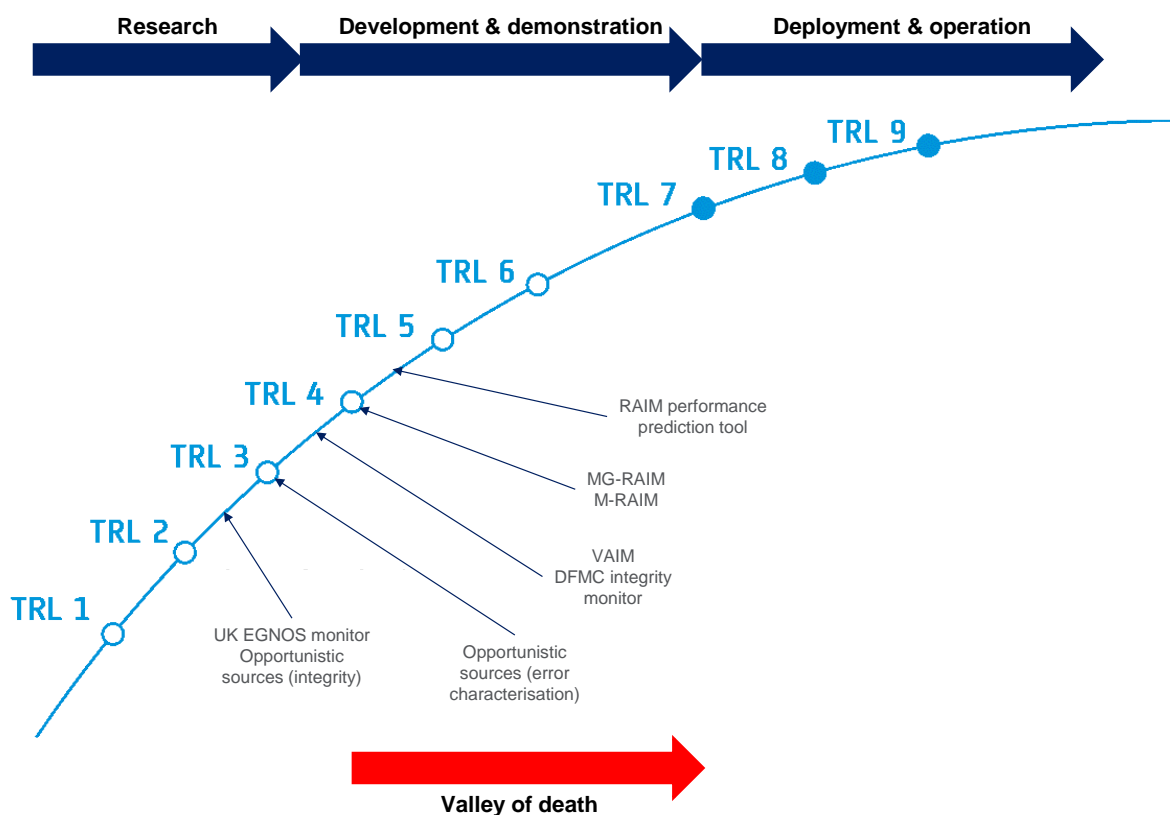


Figure 19 - TRL of the INSPIRe integrity concepts, illustrating the "valley of death".

As illustrated in Figure 19, INSPIRe has raised the maturity of its integrity concepts to between TRL 2 to 3 for the more immature concepts, and to between TRL 4 to 5 for the more mature concepts.

Further development to deployment and operation will require the concepts to cross the so-called valley of death between TRLs four and seven, the gap between academic or upstream research and commercialization. This part of the innovation path can be problematic to fund because it falls between the regime where public-funded research is legitimate and the regime where industry can be expected to make a reasonable rate of turn relatively quickly.

The new UK PNT framework, together with ESA's NAVISP programme elements 1 and 2 provide potential mechanisms for addressing funding needs to progress INSPIRe's more promising concepts towards the market.

### 11.7.2 Standards development

Those components of INSPIRe's concepts that require operational onboard equipment to be fitted to commercial (SOLAS) vessels – MG-RAIM, M-RAIM, VAIM – will likely need to follow the global maritime standardisation process for onboard equipment. The contracting state will make a proposal to the IMO concerning the onboard equipment, if accepted the IMO will develop and publish performance requirements which will be used to develop test specifications by the IEC as the basis for industry to develop equipment. INSPIRe's results, particularly algorithms, can form the basis and starting point for the development of MG-RAIM, M-RAIM and VAIM standards.

Those components of INSPIRe's concepts that involve transmission of data from shore-to-ship will also need to follow a similar but slightly different standardisation process. Here, IALA is the lead on standards development and will define the service performance requirements. This will then be taken on by RTCM (and potentially ITU) to develop signal-in-space characteristics, which will be used by industry to define the shore-based and onboard equipment.

The precise path to standardisation will depend on the detail of the use case being considered but the important points are:

- The concept must be standardised at international level following a potentially heavy, cumbersome and lengthy process, contributing to the risk of the valley of death.
- The support from at least one national maritime administration is needed to start the process. The support will need to grow to a majority of the voting members in IMO and IALA to be successful.

The concepts and algorithms developed by INSPIRe provide a sound platform for the start of the standardisation but will need national support to progress. As with other areas, the UK's new framework for PNT might provide an opportunity/entry point for INSPIRe into the standardisation process.

### ***11.7.3 Opportunities for industry***

D10.1 provides a summary suggesting that merchant navigation, which is the category that most closely fits the SOLAS general navigation market segment has remained flat between 2012 and 2022. This is the segment where MG-RAIM, M-RAIM and VAIM are most likely to be mandated.

It highlights that the recreational sector is by far the largest with over one million units sold per year, however although the INSPIRe concepts are unlikely to be mandated for this sector it still may provide the largest market opportunity as recreational navigators choose voluntarily to equip their vessels with top-of-the-range equipment.

## **11.8 Beyond INSPIRe – opportunities outside the maritime sector**

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### ***11.8.1 Outside the maritime sector***

INSPIRe has focused on use cases and performance requirements in the maritime sector. However, opportunities for improved integrity exist in other sectors where PNT performance is critical to successful operations and where there is risk of severe negative consequences in one or more performance dimensions.

The primary markets where integrity concepts investigated by INSPIRe could be applied include:

- uncrewed aerial systems (UASs)/remotely piloted air systems (RPAS) and urban air mobility (UAM), that operate in complex geometries, multipath and shadowing, varied platform geometries (e.g. vertical take-off and landing (VTOL), hover, sideways motion, etc) and electromagnetic compatibility environments, such as cityscapes akin to those experienced on ships and in ports, where the concepts and technologies applied in the broader aviation sector break down;
- sectors that use UAS/RPAS operationally, such as survey, offshore exploration and exploitation, and agriculture;
- the road transport sector, especially for highly connected autonomous vehicles that will likely operate in urban canyon environments where large numbers of satellites are masked from view by buildings and multipath is prevalent.

Specifically, the crowd-sourcing concepts that INSPIRe has explored will be applicable to situations where there is a large number of cooperative platforms that need and use high performance PNT. This will include aviation for networked air traffic management, highly connected autonomous vehicles, geodetic reference systems and, potentially, many others.

Further details on the application of integrity concepts to other sections can be found in D10.1.

## 12 COST BENEFIT ANALYSIS

The Cost-Benefit Analysis considers a number of use cases in the maritime domain, with a primary focus on the socio-economic benefits that these use cases generate for the UK and how these are impacted in scenarios where integrity information could be critical for operations.

The use cases are drawn from Work Package 1 of the INSPIRe project. INSPIRe has classified maritime use cases according to integrity need by attributing each use case to navigation phase performance bands established by the International Maritime Organisation's (IMO's) standards A.1046 and A.915.

The CBA considers the central economic case of the wider UK socio-economic benefits. The benefits measured account for the difference between the estimated loss of economic value resulting from the specified integrity failure events and the reduction in this estimated loss attributable to the INSPIRe solution.

Three separate approaches to providing integrity as part of the INSPIRe solution have been investigated elsewhere in the INSPIRe project and reported in Work packages 5, 6 and 7. The analysis presented in this CBA considers the ability of each of these to provide sufficient integrity information for each use case, with their respective estimated development timelines and theoretical capabilities serving as critical inputs.

### 12.1 Methodology

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In this analysis we draw on estimated costs associated with the development of various approaches to delivering the INSPIRe integrity functionality. These costs are compared with the benefit such a functionality would provide to the UK maritime industry. These benefits are specifically the socio-economic loss that is avoided in the event of specified integrity events.

A scenario-based approach is used to estimate the costs and avoided loss of economic value. The definition of these integrity events is considered in more detail in Section 15.4.

Given that costs and benefits are distributed over time, it is necessary to discount their value to account for the time value of money, and thereby ensure comparability. We follow standard UK Government practice as specified in The Green Book to compute the Net Present Value (NPV) - the difference between discounted benefits and discounted costs. The results of the analysis also include the benefit-cost ratio (BCR) which can be used to compare the relative profitability of projects. If the resulting BCR is greater than one this indicates that the project is economically worthwhile; if it is less than one then it is recommended that alternative projects are investigated.

### 12.2 Technical inputs

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The technical work packages of INSPIRe provided development costs and timelines, as well as other inputs, which were used for the CBA. The following INSPIRe project areas were used:

- **Requirements Capture** - provided a set of use cases considered applicable to INSPIRe. The use case activities focus on above-water vessel operations and have been down-selected for this report to only those where integrity need was found to be 'High' on a 'High-Moderate-Low' scale were assessed in this report.
- **EGNOS Monitoring Solution** - Guidance on an indicative development timeline suggests that such an EGNOS monitoring service network could be built within two years of the end of the INSPIRe project. However, zero practical functionality is expected from the system until Satellite-Based Augmentation System (SBAS) aviation approaches are re-established in the UK therefore it is expected to provide zero functionality until 2027 – when it begins to deliver 100% of its potential.

- **RAIM Availability prediction tool** - The development timeline is modelled as the M(G)RAIM solution providing 0% of its potential to users until at least 18 months following the end of the current INSPIRe project – set as 2026. Following this we model 90% of potential functionality as being provided, growing rapidly over the next 2 years to 100% in 2028 as the proposed solution finishes development.
- **DFMC Integrity Monitor** - The system is expected to have an approximately 6-year development timeline to full operational capacity, with no operational capacity expected before this point. This is specifically modelled as a 6-year development period 2024-2029 followed by 20% achievement of potential 2030-2032 and 100% achievement of potential from 2033 onwards.

Table 4 - Collated INSPIRe development timelines

Proposed solution	2024	'25	'26	'27	'28	'29	'30	'31	'32	'33	'34	'35
EGNOS monitoring service	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%
RAIM availability prediction tool	0%	0%	90%	93%	100%	100%	100%	100%	100%	100%	100%	100%
DFMC integrity monitoring	0%	0%	0%	0%	0%	0%	20%	20%	20%	100%	100%	100%

### 12.3 Integrity use cases

The INSPIRe project identified a set of use cases, as defined in Section 6, where there is both a high degree of relevance to the UK's socioeconomic interests and a (perceived) high degree of dependence on integrity information in their operations.

For all sectors, aside from ship-to-ship transfers, emergencies were identified has high integrity need use cases. Work is already being carried out by a Scottish company, Zelim, to use a network of semi-autonomous unmanned rescue vessels to save lives at sea [20].

When accidents do happen in these sectors, standard and automated Search and Rescue missions will be critically dependent on integrity information to carry out their activities.

### 12.4 Integrity failure scenarios

An integrity failure event is when an integrity event occurs and no alarm is raised within the acceptable 'time to alert'. This means that the position information provided by a navigation system has been unreliable for so long that the user's reliance upon it is creating material risk. These integrity failure events can have multiple causes, to which this report is agnostic.

The overarching goal with integrity failure scenarios design was to achieve the following:

1. Cover the various use cases identified in this INSPIRe project such that the theoretical technical impact of an integrity failure event on each can be estimated;
2. Align theoretical use case impacts due to the scenarios to the reality of the UK maritime sector by identifying real hubs for marine activities, enabling...
3. Hypothetical scenarios developed that map to real-world impacts and hence evidence-based estimates of socio-economic impact from integrity failure scenarios

With these goals serving as guidance, two distinct scenarios were developed.

In each case they are **assumed to be entirely unexpected**, meaning that the use cases are entirely dependent on the systems they have in place at the time.

**Each integrity failure scenario is assumed to last 1 week** at an unspecified point in each year of the analysis period. This enables assessment of current, emerging, and future use cases against the developing profile of INSPIRe solutions as time passes.

Of relevance for both scenarios is the UK's exclusive economic zone.

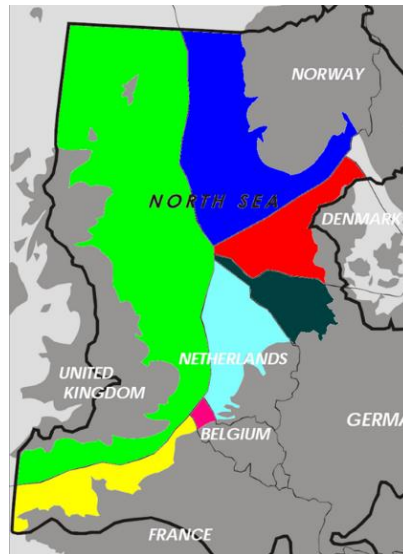


Figure 20 - UK Exclusive Economic Zone relevant to Scenarios 1 and 2 (marked in green)

Source: Wikimedia Commons

#### 12.4.1 Scenario 1: North Sea integrity failure

The first scenario is assumed to take place off the English coast. Specifically, a 125km radius circle, centred on the English coastline due north of Norwich (i.e. approximately the coastal town of Cromer), defines the affected area. This circle encompasses the Lincolnshire and Norfolk coasts, the Wash bay, the mouth of the Humber tidal estuary, and approximately 30,000 square kilometres of North Sea where the UK has an exclusive economic zone.

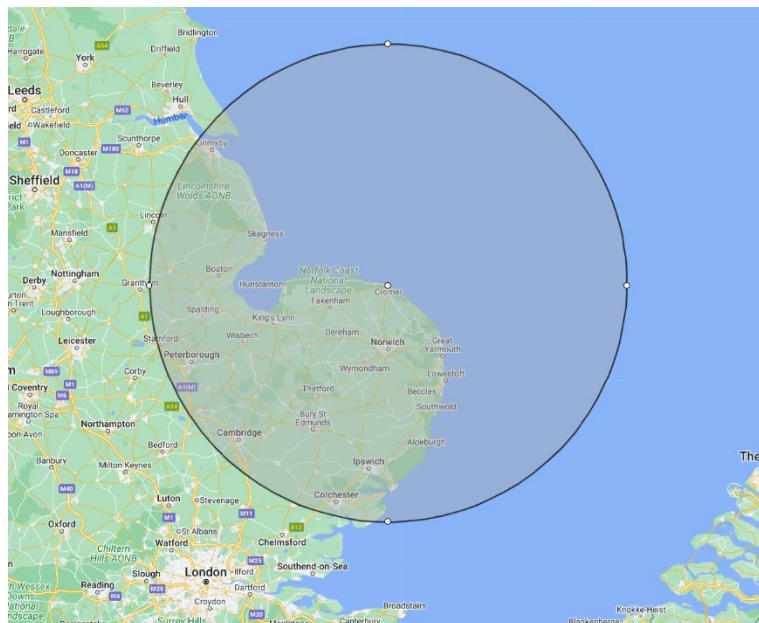


Figure 21 - Scenario 1: North Sea integrity failure affected area

The area is home to approximately 15 active ports, and to a significant portion of the UK's maritime economic activities.

### 12.4.2 Scenario 2: Orkney Archipelago integrity failure

The second scenario is assumed to take place off Great Britain's north-eastern tip, in the Orkney Archipelago. Specifically, a 50km radius circle centred on the Rousay, the sixth-largest of around 70 islands making up the Orkney Islands, defines the affected area. This circle encompasses all the Orkney islands, six separate Marine Protected Areas, four active ports, and a wealth of natural resources.



Figure 22 - Scenario 2: Orkney Archipelago integrity failure affected area

## 12.5 Economic Value generated by integrity use cases

### 12.5.1 Approach

This section will summarise an assessment of the socio-economic value generated by each use case. This value is estimated for the 20-year period of 2024-2043 (inclusive). Two sources of socio-economic value are estimated: operational value and emergencies. For emergencies, this is estimated by calculating the value that would be generated if the accidents that occur in a year were avoided. Approximately 10 serious injuries per year one death every 5 years occur in incidents relating to SAR vessels in the UK. In multiple cases the ratio of use case GVA contribution relative to the total UK maritime GVA is used to apportion these accidents to different use cases, and the value of avoiding these incidents is determined using UK Government figures for the value of prevention of road casualties [33].

### 12.5.2 Aquaculture

Aquaculture operational benefits and emergencies costs will be assessed for the Orkney region. A 9% share of (Scotland) aquaculture GVA is allocated to Orkney using Orkney's share of Scottish salmon farming [21]. This amounts to a nominal GVA of £1.1bn over the 20-year period. The estimated value of avoiding SAR injuries and deaths in Orkney aquaculture can be monetised at approximately £89,000 in nominal terms over the period 2024-2043.

### 12.5.3 Ship-to-Ship

Ship-to-ship operational benefits will be assessed for the Orkney region. Scapa Flow statistics for recent years indicate oil port revenues of £2-3m per year. These are partially derived from the 70-80 STS transfers conducted each year, and we allocate 20% of the revenues to such transfers giving an estimated £19.2m expected over the 2024-2043 period.

#### **12.5.4 Ocean Energy**

Ocean energy emergency costs will be assessed for the Orkney Archipelago. Orkney's tidal and ocean energy sector is estimated to have contributed around £130m of GVA 2003-2023 [22], at a rate of around £6.5m per year. The estimated emergencies costs can be monetised at approximately £13,000 in nominal terms over the period 2024-2043.

#### **12.5.5 Fisheries**

Fisheries emergencies costs will be assessed for the Orkney Archipelago. Orkney's fisheries sector is estimated to have contributed around £8m of GVA in 2021 [23]. This is used to apportion three sources of emergencies costs to Orkney's fisheries: Fishery-specific damage to human life (30 injuries, 5 deaths per year [28] SAR vessel incidents; and lost fishing vessels (1 vessel per year in the UK). In combination, the value of avoiding these accidents can be monetised at approximately £34.9m in nominal terms over the period 2024-2043.

#### **12.5.6 Bio-economy**

Bio-economy operational benefits and emergencies costs will be assessed for the Orkney Archipelago. 10% of the benefits of banning bottom-trawling in Scottish MPAs are apportioned to Orkney, amounting to £82.2m over the 20 years from 2024 in nominal terms. Apportioning SAR vessel injuries and deaths by this £82.2m results in approximately £171,000 of emergencies cost over the period 2024-2043.

#### **12.5.7 Offshore Wind**

Offshore wind emergencies costs will be assessed for the North Sea area. Scenario 1's North Sea area offshore wind energy sector has an estimated value of approximately £300m per year [24]. The estimated value of avoiding SAR injuries and deaths in this sector and area can be monetised at approximately £574,000 in nominal terms over the period 2024-2043.

#### **12.5.8 Offshore Oil and Gas**

Operational benefits and emergencies costs for offshore oil and gas are assessed for the North Sea area. North Sea offshore oil and gas represents approximately 66% [25] of the 2022 UK total GVA of £30.2bn [26]. The projected GVA produced over the period 2024-2043 amounts to £304bn in nominal terms. Each year there are approximately 180 emergency medevacs via helicopter [27] from UK oil or gas rigs. We estimate approximately 120 accidents within the focus area per year, costing around £10,000 per trip [29]. Adding this to the estimated cost of SAR incidents attributable to this sector and area gives emergencies costs of £41.1m.

#### **12.5.9 Carbon Capture**

Operational benefits and emergencies cost for carbon capture and storage are assessed for the North Sea area. The whole-UK GVA contribution of CCS is expected to peak at around £5.9bn in 2040 [30]. The estimated GVA of the Humber area generated over the 2024-2043 period is equal to £17.6bn in nominal terms. The emergencies costs can be monetised at approximately £1.9m in nominal terms over the period 2024-2043.

#### **12.5.10 Marine Autonomous Surface Ships: ocean transport**

MASS cost savings per year are estimated at 3.4% [31] and the UK's value generated from ocean-phase shipping estimated at around £6.2bn in 2024. With a growing share of UK ships assumed to be MASS, the total economic value of these ships to the UK in nominal terms over the period 2024-2043 is estimated at slightly over £2bn.

### 12.5.11 Integrity use cases: value summary

The average cost of an investigation into a marine accident is £30,000 [32]. Around 20 investigations are started per year, giving an additional £12m in emergencies costs over the 20 years. In total £329bn operations benefits and £90.7m emergencies costs are considered within scope for this analysis. £1.3bn are located in the Orkney Archipelago and £325.7bn in the North Sea area defined in Scenario 1.

## 12.6 Economic impact: Scenario analysis

### 12.6.1 Approach

This section applies the scenarios defined in Section 15.4 to the use cases modelled in Section 7 to understand the impact of a loss of integrity information on the use cases' abilities to continue to deliver socio-economic value. Estimates are provided of the evolving share of benefits generated by each use case that are dependent on integrity information.

Importantly, the degree to which each of the technologies explored as part of INSPIRe can potentially mitigate these socio-economic losses will also be estimated. This degree of mitigation will be based on multiple factors, including:

- Binary (Yes/No) selection on whether the technology is capable of fulfilling the user accuracy requirement for that use case
- Percentage contribution estimate (0-100%) based on system functionality from development schedule (see Section 4 for more detail)

Mitigated socio-economic losses attributable to the INSPIRe solution(s) will be considered economic benefits that could realistically be generated by INSPIRe. The only use cases where INSPIRe is not expected to deliver the required level of accuracy are for offshore oil and gas, carbon capture and storage, and ship-to-ship transfer operations. The outputs from these models are summarised in Table 5.

Table 5 - Benefit estimations summary (nominal terms, £m)

Scenario	Use case	Category	Geography	Economic value generated	Potential integrity benefits	Scenario-driven potential INSPIRe benefits
1	Offshore wind	Emergencies	North Sea	£0.6	£0.3	£0.2
1	Offshore oil and gas	Operations	North Sea	£304,137	£28	-
1	Offshore oil and gas	Emergencies	North Sea	£41	£0.5	£0.4
1	Carbon capture and storage	Operations	North Sea	£17,629	£2,526	-
1	Carbon capture and storage	Emergencies	North Sea	£1.9	£0.5	£0.4
2	Ship-to-ship	Operations	Orkney	£19	£14	£-
2	Ocean energy	Emergencies	Orkney	£0.01	£0.01	£0.01
2	Aquaculture	Operations	Orkney	£1,125	£1.4	£1.3

Scenario	Use case	Category	Geography	Economic value generated	Potential integrity benefits	Scenario-driven potential INSPIRe benefits
2	Aquaculture	Emergencies	Orkney	£0.1	£0.0	£0.0
2	Fisheries	Emergencies	Orkney	£35	£18.8	£16.8
2	Bio-economy	Operations	Orkney	£82	£6.7	£6.1
2	Bio-economy	Emergencies	Orkney	£0.2	£0.1	£0.1
2	Marine investigations	Investigations	Both	£12	£6.0	£5.1
	Total			£323,083	£2,603	£30

### 12.6.2 Economic impact: broader picture

It is also valuable to consider the impact of such scenarios if the geographical restriction is lifted and the integrity events occurred at a national scale – the same scale at which INSPIRe could be provided.

The share of each use case and specific geographic context, i.e. “aquaculture in the Orkney Archipelago” has been estimated (see the table below). These figures are used as scaling factors to approximate the value to the UK as a whole if an integrity failure event were to impact the entire country rather than the (more realistic) geographically-bound scenarios.

In this section the value of MASS is included, as this is considered at a national level rather than within either of the geographically-bound scenarios. These benefits are estimated at a nominal value of £859m.

Table 6 - Use case market shares and results of scaling to whole-UK figures

Use case	Geography	Share of UK market	INSPIRe value, base case (£m)	INSPIRe value, whole UK (£m)
Aquaculture	Orkney Archipelago	8%	1.29	16.5
Ship-to-ship	Orkney Archipelago	5%	0	0
Ocean energy	Orkney Archipelago	10%	0.006	0.06
Fisheries	Orkney Archipelago	1.5%	16.8	1,105
Bio-economy	Orkney Archipelago	2.5%	6.2	247
Offshore Windfarms	North Sea defined area	30%	0.24	0.80
Offshore Oil & Gas	North Sea defined area	66%	0.39	0.59
Carbon Capture and Storage	North Sea defined area	20%	0.38	1.96
Marine Investigations	n.a.	100%	5.13	5.13

### **12.6.3 Summary**

Across the 8 sectors and 13 use cases identified as part of this study, over £2.6bn of potential integrity benefits were identified. Of these, just £30m are estimated to be within scope for INSPIRe and the two scenarios defined as part of this study.

The majority of benefits that are expected to accrue to INSPIRe come from reduced emergencies activities in fisheries and the protection of Marine Protection Areas from bottom-trawlers (contributing a combined £23m of £30m total).

When expanding the use cases considered to a national scale, using appropriate scaling factors that account for the defined scenarios' share of their total UK markets, a total of £2.2bn of potential INSPIRe benefits are estimated over the 20-year period.

## **12.7 Consolidated costs**

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### **12.7.1 High-level summary**

Costs are considered for the 2024-2048 period as this is the expected lifetime of the DFMC Integrity Monitoring service without further CAPEX.

The total costs for the three proposed INSPIRe technologies over this period are a little over £275m. Breaking this down by technology, we have:

- EGNOS Monitor Network: £5.8m
- M(G)RAIM performance prediction tool: £2.7m - £6.1m
- DFMC Integrity Monitoring Service: £265.5m

The average cost per year over a 25 year period from 2024 is slightly over £11m. Excluding the DFMC Integrity Monitoring service this average cost per year falls to £402,000.

The M(G)RAIM performance prediction tool has two possible versions; without a Quality of Service commitment expected OPEX is 5x lower, as less expenditure is anticipated on e.g. a helpdesk.

### **12.7.2 Timeline of capital and operational expenditures**

The chart below highlights how the DFMC service dominates expected expenditure on development of INSPIRe over the period 2024-2048.

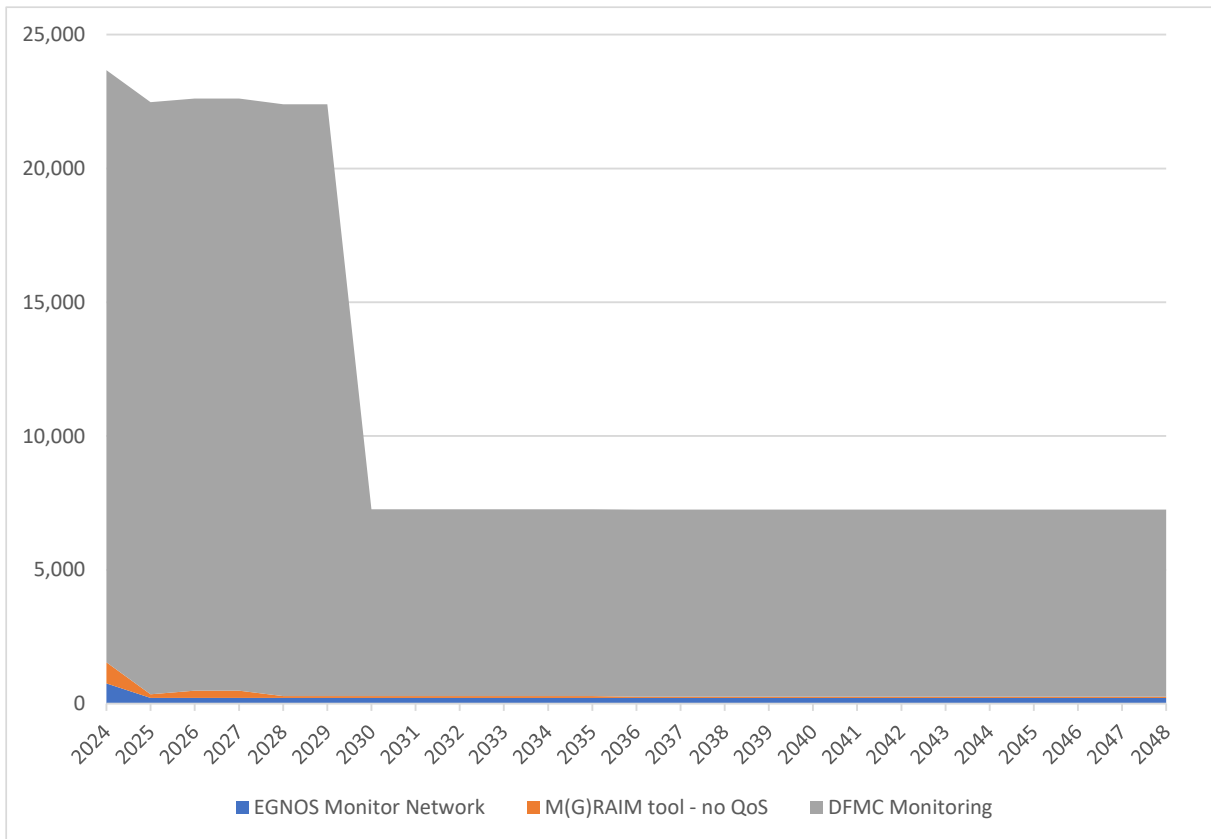


Figure 23 - CAPEX and OPEX schedule, INSPIRe development

Another two charts illustrating the M(G)RAIM tool with and without QoS are included below, with DFMC removed so that the different profiles are more readily visible.

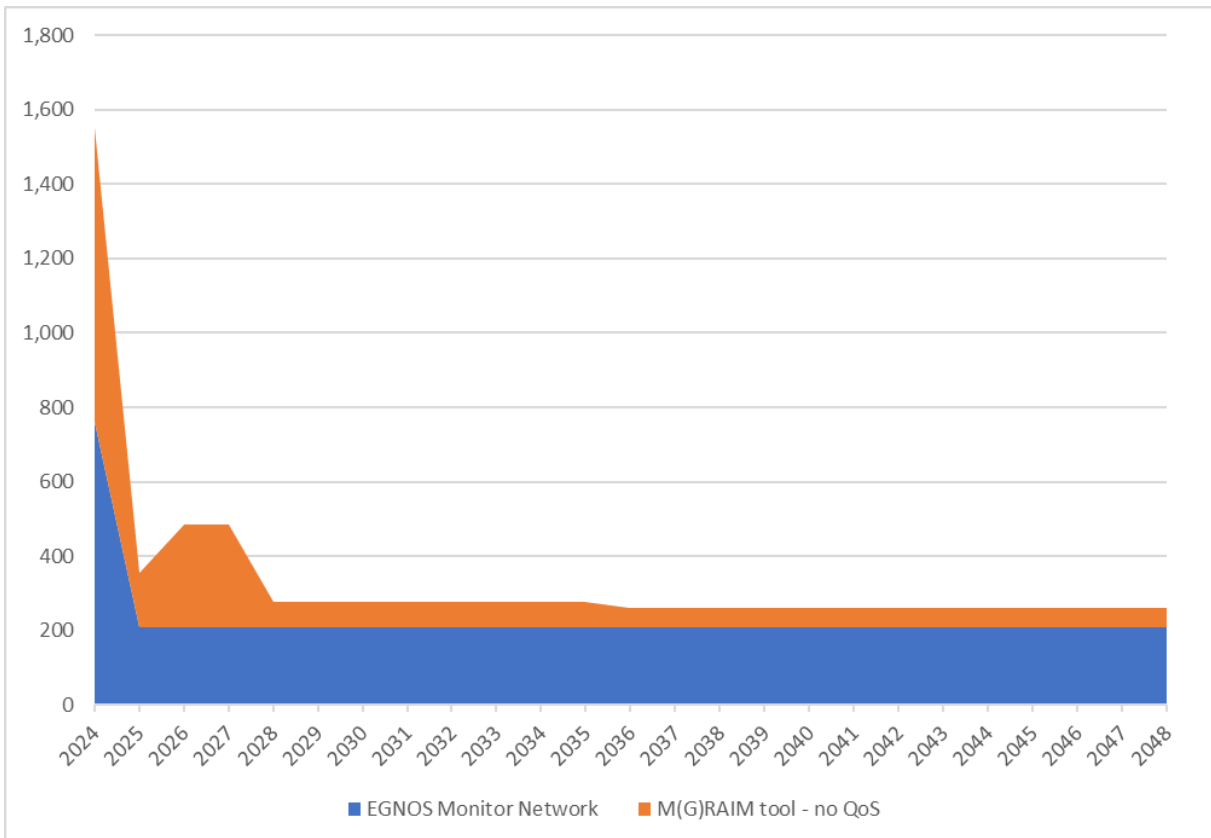


Figure 24 - CAPEX and OPEX schedule, INSPIRe development - excluding DFMC Monitoring Service, no QoS commitment

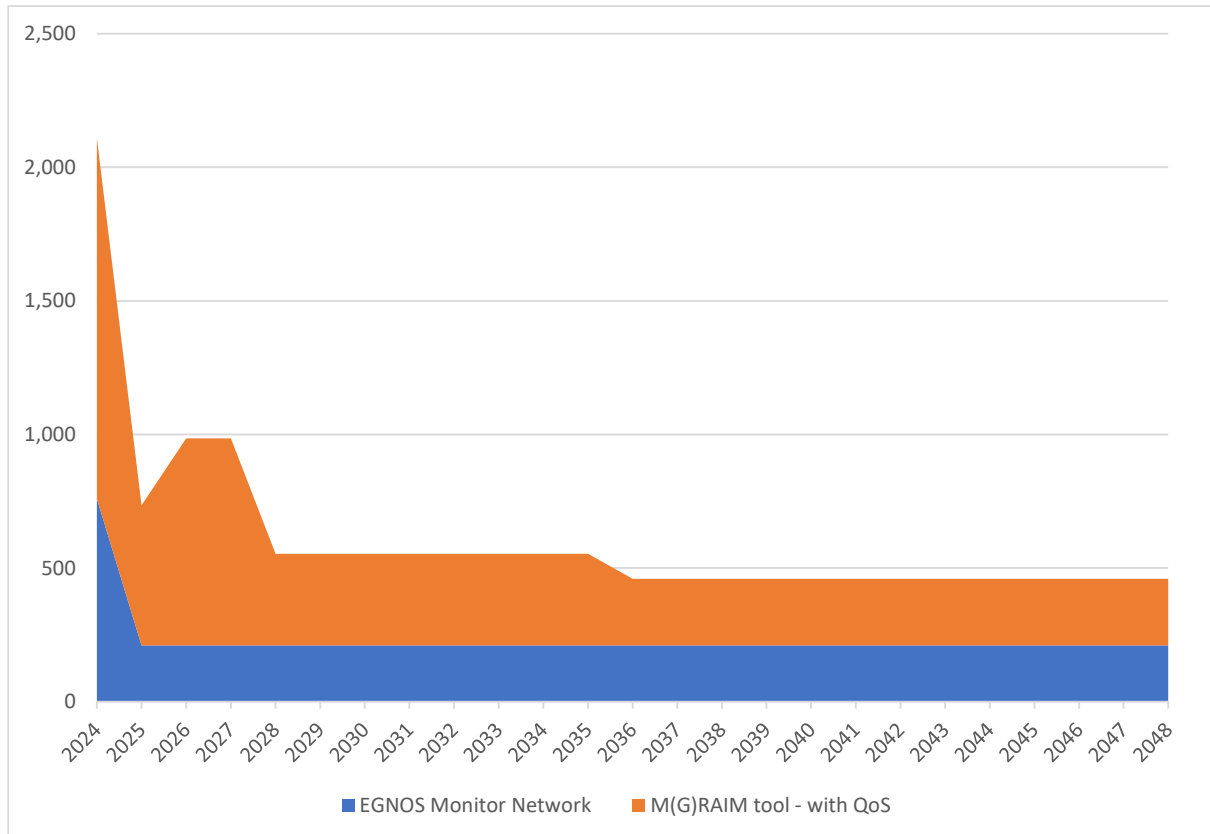


Figure 25 - CAPEX and OPEX schedule, INSPIRe development - excluding DFMC Monitoring Service, with QoS commitment

## 12.8 High-level Cost Benefit Analysis

To compare the costs and benefits of INSPIRe a Cost Benefit Analysis was conducted. A discount rate of 3.5% per year is used in line with HMG’s Green Book, and 2024 is used as the base year.

### 12.8.1 Benefits

Across the 20 years 2024-2043, INSPIRe is capable of mitigating a total of £30m of socio-economic losses due to annual recurring integrity failure scenarios.

A further case is considered, whereby these benefits are scaled to a national scale. In this national case the estimated INSPIRe mitigation is valued at £2,237m. Marine Autonomous Surface Ships are included in this national-level estimate.

The annualised rate of benefits accrual increases over time as the modelled dependence on integrity increases. A key cause of this is an increase in automation across many sectors.

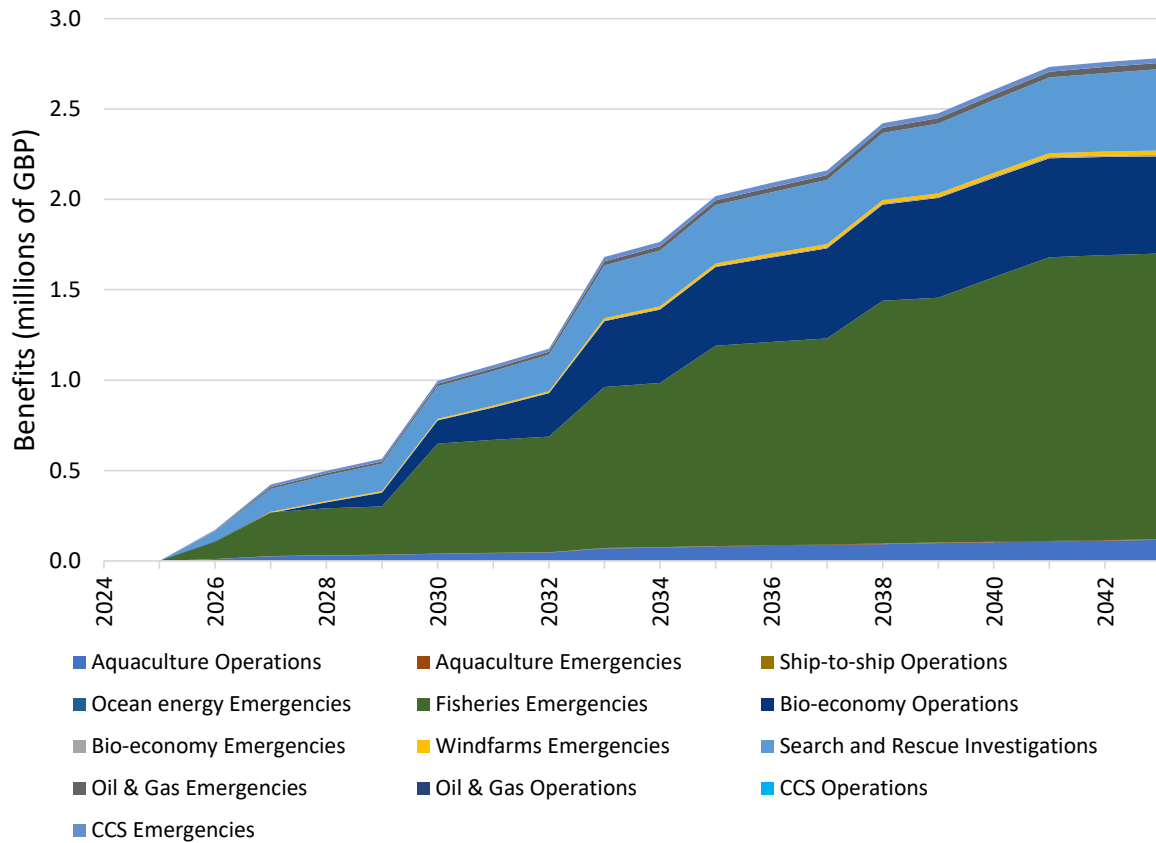


Figure 26 - Annual benefits from INSPIRe mitigation of integrity failure events

In present value terms the benefits are estimated at £18.9m in the scenario-driven case, and £1,371m in the nationally extended case.

### 12.8.2 Costs

The total costs for the three proposed INSPIRe technologies over this period are almost £242.5m when taking the mean value for the M(G)RAIM's two different options. Breaking this down by technology, we have:

- EGNOS Monitor Network: £5.8m
- M(G)RAIM performance prediction tool: £2.7m - £6.1m
- DFMC Integrity Monitoring Service: £265.5m

These costs are greatest early in the development phase, due to CAPEX requirements, and fall over time to a steady level of OPEX-driven costs (see Figure 23).

In present value terms the costs are estimated at £194m.

### 12.8.3 Cost Benefit Analysis

The Net Present Value of investment in INSPIRe is below zero for the scenario-driven case (-£175m) but positive for the nationally extended case (£1,177m).

The Benefit:Cost ratio delivered by INSPIRe is 0.10 for the scenario-driven case and 7.06 for the nationally extended case.

These results emphasise the need for a national service rather than a geographically contained solution, as this significantly improves the Net Present Value and cost-benefit ratio due to more of the UK's marine economy being within scope.

The importance of (not) meeting user accuracy requirements for key marine sectors is clear when considering the vast potential benefits that are not captured in either of the oil and gas or carbon capture and storage sectors.

It is also important to note that the analysis only considered use cases where integrity was considered a high priority – many others were discarded at this stage. Further research could add value to this study by expanding the scope of the study to include these additional use cases.

## **12.9 Conclusion**

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13 distinct use cases across 8 sectors within the UK marine economy have been explored, and MASS in addition to this, and how each of them could be impacted by outages centred on the Orkney Archipelago and in the North Sea off the Norfolk coast. These use cases were sourced from Work Package 1, where they were marked as 'high' on an integrity information dependence scale.

The costs of developing three different monitoring technologies were collated: an EGNOS monitoring service, a RAIM availability prediction tool, and a Dual Frequency Multi-constellation Integrity Monitoring service.

Key results include that INSPIRe is estimated to have a Benefit:Cost ratio of less than 1 for the scenario-based analysis that focused on two contained geographical areas. The same ratio was, however, above 7 for an extrapolation of these results to the national (UK) level.

One key driver of these results was the selection of only 'high' integrity need use-cases for economic analysis. A broader set of use cases may yet reveal significant additional benefits for the INSPIRe service. Another important factor was INSPIRe's inability to deliver to the required user accuracy for both the 'oil and gas' and 'carbon capture and storage' sectors; the two largest contributors to UK marine GVA.

## 13 SUMMARY AND CONCLUSIONS

This report summarises the INSPIRe project, providing context for integrity within the maritime sector, summarises the approach to developing an integrity solution giving a high-level view of the integrity concepts developed at both the user-level and at the system-level and the route for the implementation and exploitation.

### 13.1 Technical Work Package Summary

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INSPIRe has developed solutions that validated well against core functional and non-functional requirements.

INSPIRe tested a range of user-level solutions of different underlying complexity, ranging from those intended to be implementable in the near-term whilst offering material benefit over current approaches (MG-RAIM), and those that may offer even greater functional and performance benefits but have a medium-to-long term implementation scale and require a better characterisation of the local maritime environment (M-RAIM and VAIM). Single constellation and DFMC variants were tested, and the benefits of augmentation analysed.

Overall, INSPIRe shows a series of solutions that are able to address increasingly stringent performance requirements, and are able to cover a wider set of current and future functional requirements – describing an evolution of integrity monitoring approaches from today to more sophisticated future implementations. This context can be aligned with expectations for an increasingly complex maritime environment including growing use of autonomous systems – both of which will drive the need for better integrity monitoring. Importantly, though, MG-RAIM shows a way to improve maritime integrity monitoring rapidly, and in pursuing the long-term vision we should not create impediments to improving safety and operational efficiency today.

As we look to next steps, focus is needed in four areas:

- Developing an approach to characterising errors from the local maritime environment that is able to cover the gamut of sea-states and vessel configurations with high confidence, and without excessive overbounding;
- Finalising the requirements set for integrity monitoring by addressing the remaining ambiguities and establishing an agreed, ideally standardised, level of integrity performance from the user perspective;
- Exploring emerging methods to improve integrity monitoring performance including research into more representative error distributions, and more novel integrity sources such as signals of opportunity; and,
- Continuing to advance MG-RAIM, M-RAIM and VAIM through technology readiness levels (TRLs) towards deployment, with a focus on testing algorithm performance in real-world environments, either through integration with vessel systems at scale, or testing with significantly greater real-world data quantities representing all possible maritime environments.

The work in INSPIRe has demonstrated the feasibility of improved approaches to maritime integrity monitoring and the benefits these provide. Concerted efforts in these four key areas will be essential to driving the approaches developed here through to TRL 9+ and to wide adoption by maritime vessels. The need for resilience in PNT is ever increasing, and the provision of better maritime integrity will be a necessary underpinning to achieving this.

### 13.2 Implementation and Exploitation Summary

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The functionality and performance currently demonstrated by INSPIRe's integrity architecture is shown to provide net socio-economic benefits of up to £2.2bn over a 20-year period when applied to key current and developing use cases in the maritime sector. This benefit is

achieved by alerting the mariner when there is a loss of integrity of their GNSS navigation solution, enabling them to mitigate otherwise critical loss scenarios.

The benefits of the integrity architecture can be further expanded, both by improving its performance to widen applicable use cases, and by applying the architecture to other sectors; such as UAVs, connected and autonomous vehicles, peer-to-peer networks, and other sectors.

An implementation roadmap sets out the workstreams required to realise INSPIRe’s integrity architecture in the maritime sector. It aims to enable near-immediate adoption of user-level integrity in non-regulated markets and a longer-term adoption in the regulated SOLAS market as maritime navigation standards are developed and implemented.

The roadmap demonstrates opportunities to co-ordinate work streams as the integrity concepts are developed to reduce the implementation timelines and costs, and to set out a common institutional framework. It also provides opportunities for using the non-regulated sector as an ongoing demonstration of the integrity architecture to support further technical development and standards deployment.

The key workstreams required to implement the INSPIRe integrity architecture are:

- Continued development of the integrity concepts to maturity
- Establishing the necessary institutional frameworks
- Developing international user-level standards
- Implementing the system-level integrity concepts and supporting tools
- Fostering adoption of the integrity concepts in maritime and other sectors

	Duration	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
<b>Developing the integrity concepts to maturity</b>													
Peer review of integrity concepts	0.5 years	█											
Data collection for characterising the maritime environment	5 years	█	█	█	█	█	█	█	█	█	█	█	█
DIM message development	1 year	█											
Testing and validation of user-level performance	Ongoing	█	█	█	█	█	█	█	█	█	█	█	█
Research to develop performance improvements	Ongoing	█	█	█	█	█	█	█	█	█	█	█	█
<b>Developing the institutional framework</b>													
Attribute responsibilities to UK Competent Authorities and Certification Bodies	1 year	█											
Certification and safety-of-life assurance activities	Ongoing	█	█	█	█	█	█	█	█	█	█	█	█
Manage project implementations	Ongoing	█	█	█	█	█	█	█	█	█	█	█	█
<b>Developing international user-level standards</b>													
Gathering national and international support for developing standards	1-2 years	█	█										
Developing IMO ConOps and user-requirements for navigation	4-6 years	█	█	█	█	█	█	█	█	█	█	█	█
Developing IMO generic GNSS receiver functional and performance standards	4-6 years	█	█	█	█	█	█	█	█	█	█	█	█
Developing IEC specifications for equipment certification incorporating MG-RAIM	4-6 years	█	█	█	█	█	█	█	█	█	█	█	█
Developing IEC specifications for equipment certification incorporating M-RAIM	4-6 years	█	█	█	█	█	█	█	█	█	█	█	█
<b>Implementing national system-level integrity concepts and supporting tools</b>													
RAIM Prediction Tool	2 years	█	█										
EGNOS Monitor (SoL service)	3 years	█	█	█									
DIM (non-SoL service)	5 years	█	█	█	█	█	█	█	█	█	█	█	█
DIM (SoL service)	+3 years	█	█	█	█	█	█	█	█	█	█	█	█
Dissemination system (e-Navigation services) *note, outside of INSPIRe scope	5 years	█	█	█	█	█	█	█	█	█	█	█	█
<b>Fostering adoption of the user-level integrity concepts</b>													
Promotion of the integrity concepts to maritime and other sectors	Ongoing	█	█	█	█	█	█	█	█	█	█	█	█
Adoption in the leisure market and for specialised use cases	Ongoing	█	█	█	█	█	█	█	█	█	█	█	█
Adoption in the regulated SOLAS market for general navigation	Ongoing	█	█	█	█	█	█	█	█	█	█	█	█

Figure 27 - Implementation roadmap for INSPIRe integrity architecture

There are various dependencies which lead to uncertainty in this roadmap, notably including modelling the maritime environment, gathering the industry support required to put forwards international standards, and consultation processes.

It is therefore critical to realise these workstreams in partnership with users, industry and other relevant stakeholders both nationally and internationally to ensure that requirements are formalised in line with user needs, an architecture is developed in line with requirements, and safety and performance can be assured to the necessary levels.

## 14 APPENDIX A – EXTERNAL STAKEHOLDER ENGAGEMENTS

Engagement Meeting	Purpose	Date
Meeting with EGNSS-R TREN railway GNSS safety standards	Share aims and objectives of the TREN EGNSS-R project	October 2022
Presentation from INMARSAT on UK SBAS	Introduce INSPIRe and raise awareness	March 2023
Hybrid consultation event	Present results to date and capture views on maritime integrity	February 2023
INSPIRe promoted at RIN event on LEO PNT	Introduce INSPIRe and raise awareness	February 2023
Virtual meeting with Ordnance Survey on collaboration	Exploring collaboration and data sources to be used in the project	May/June 2023
INSPIRe and SBAS alignment meeting	Exploring collaboration in the project	November 2023
GMV presentation at the European Navigation Conference	Raise awareness of INSPIRe and share work on user algorithms	May 2024
NAVISP Webinar	Provide an update and share project results	June 2024