INSPIRe Integrity

System Development and Implementation Plan

D10.1 WP10 Report

v2.0

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1 INTRODUCTION

INSPIRe developed and implemented concepts for monitoring the integrity of a maritime user's GNSS positioning solution.

The integrity concepts demonstrate components of a future GNSS based integrity architecture. Various integrity concepts were developed across the user-level (as ship-borne receiver algorithms), system-level (as shore-based monitoring), and as supporting tools.

By providing integrity monitoring capabilities, integrity failures can be alerted to, and thus mitigated by, the mariner. This enables increased trust in GNSS based positioning to enable, and improve the safety of, use cases with a high mission criticality.

This report identifies the future work required to implement these integrity concepts and identifies opportunities to exploit the integrity architecture within maritime and other sectors.

- Section 3 summarises INSPIRe's conceptual architecture, and identifies the current maturity and performance of each integrity concept;
- Section 4 identifies the activities required to mature the integrity concepts such that they can be implemented in an operational environment;
- Section 5 identifies the context of maritime navigation standards and explains how INSPIRe's integrity concepts can support in developing these;
- Section 6 identifies the activities required to implement the system-level integrity concepts and supporting tools;
- Section 7 presents a co-ordinated roadmap to realise INSPIRe's integrity architecture;
- Section 8 identifies opportunities to exploit the INSPIRe integrity concepts in the non-regulated maritime sector;
- Section 9 identifies opportunities to expand integrity concepts outside of the maritime sector; and
- Section 10 summarises the findings of this report.

2 REFERENCES AND ABBREVATIONS

2.1 Project Documents

Reference	Author
[1] INSPIRe Technical Proposal	Taylor Airey
[2] D1.1 Systems Engineering Report	Taylor Airey
[3] INSPIRe Test Scenario Specification	Taylor Airey
[4] INSPIRe Threats and Faults List Specification	Taylor Airey
[5] D2.1 Technical report of developments and test of GPS M(G)RAIM	GMV
[6] D3.1 Technical report of developments and test of DFMC M(G)RAIM	GMV
[7] D4.1 Technical report of developments and test of DFMC GNSS and DR VAIM	GMV
[8] D5.1 EGNOS Monitoring System Report	GRAD
[9] D6.1 RAIM Performance Prediction Prototype Tool Report	GMV
[10] D7.1 DFMC Integrity Monitoring System	CGI
[11] D8.1 Crowd-sourced sourced inputs into DFMC integrity Feasibility Report	ICL
[12] D9.1 High level Cost Benefit Analysis Report	London Economics

2.2 External References

Reference	Author
[13] ESA Technology Readiness Levels definition	ESA
[14] International Convention for the Safety of Life at Sea (SOLAS), 1974	IMO
[15] IMO Resolution A.1046 (27) adopted on 30 November 2011 WORLDWIDE RADIONAVIGATION SYSTEM	IMO
[16] IMO Resolution A.915 (22) adopted on 29 November 2001 REVISED MARITIME POLICY AND REQUIREMENTS FOR A FUTURE GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)	IMO
[17] Report on Maritime and Inland Waterways User Needs and Requirements GSA-MKD-MAR-UREQ-229399 Issue 3	EUSPA
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2.3 Acronyms and Abbreviations

Acronym	Term	Comments
AIS	Automatic Identification System	
AAM	Advanced Air Mobility	
AAM SG	Advanced Air Mobility Study Group	
ADS-B	Automatic Dependant Surveillance Broadcast	
A-RAIM	Advanced RAIM	Aviation integrity concept
ATM	Air Traffic Management	
AUGUR RAIM	Pre-flight planning for GNSS operations	Aviation integrity tool

Acronym	Term	Comments
APV-I	Approach with Vertical Guidance	Aviation approach procedure
BVLOS	Beyond Visual Line Of Sight	
CAA	Civil Aviation Authority (UK)	
CENELEC	European Committee for Electrotechnical Standardization	
CNI	Critical National Infrastructure	
ConOps	Concept of Operations	
CORS	Continuously Operating Reference Systems	
CAPEX	Capital Expenditure	
CAD	Connected and Autonomous Driving	
DAA	Detect And Aviod	
DFMC	Dual Frequency Multi Constellation	
DfT	Department for Transport	
DGLONASS	Differential GLONASS	
DGNSS	Differential GNSS	
DGPS	Differential GPS	
DIM	DFMC Integrity Monitor	INSPIRe integrity concept
DR	Dead Reckoning	
EASA	European Union Aviation Safety Agency	
EC	Electronic Conspicuity	
EDAS	EGNOS Data Access Service	
EEZ	Exclusive Economic Zone	
EGNOS	European Geostationary Navigation Overlay Service	European SBAS service
e-LORAN	Enhanced Long Range Navigation	
ESA	European Space Agency	
ESSP	European Satellite Services Provider	
ETSI	European Standards Organisation	
EUSPA	EU Agency for the Space Programme	
EUROCONTROL	European Organisation for the Safety of Air Navigation	
EVTOL	Electronically Propelled Vertical Take Off and Landing	
FLARM		Proprietary EC system in aviation
FOC	Final Operating Capability	
GEV	Generalized extreme value distribution	
GLA	General Lighthouse Authority	
GLONASS	Global'naya Navigatsionnaya Sputnikovaya Sistema	Russian satellite navigation system
GNSS	Global Navigation Satellite System	
GPS	Global Positioning System	
GPS L1	Single frequency GPS service using L1 frequency band	
GRAD	GLA Research and Development	
HEA	Harbour Entrance and Approach	
HAL	Horizontal Alert Limit	
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities	
ICAO	International Civil Aviation Organization	
ICT	Information and Communications Technology	
IEC	International Electrotechnical Commission	
IEC TC 80	IEC Technical Committee 80 - Maritime navigation and radiocommunication equipment and systems	
IGS	International GNSS Service	
IMO	International Maritime Organisation	
IMU	Inertial Measurement Unit	
INS	Inertial Navigation System	
INSPIRe	Integrated Navigation System-of-Systems PNT Integrity for Resilience	

Acronym	Term	Comments
IOC	Initial Operating Capability	
IRNSS	Indian Regional Navigation Satellite System	
ISM	Integrity Support Message	
ISO	International Standards Organization	
JARUS	Joint Authorities for Rulemaking on Unmanned Systems	
LEO-PNT	Low Earth Orbit PNT	
LiDAR	Light Detection And Ranging	
LPV-200	Localizer performance with vertical guidance	Aviation approach procedure
MCA	Maritime and Coastguard Agency	
MCC	Maritime Connectivity Consortium	
MCP	Maritime Connectivity Platform	
MF	Medium Frequency	
MG-RAIM	Maritime General RAIM	INSPIRe integrity concept
M-RAIM	Maritime RAIM	INSPIRe integrity concept
MSC	The Maritime Safety Committee	
MSI	Maritime Safety Information	
MSR	Maritime Service Registry	
MTOM	Maximum Take-Off Mass	
NAA	National Aviation Authorities	
NAVAREA	Navigational Areas	
NAVISP	ESA Navigation Innovation and Support Programme	
NMEA	National Marine Electronics Association	
NLOS	Non-Line of Sight	
OS	Ordnance Survey	
OPEX	Operational Expenditure	
P2P	Peer-to-peer integrity concepts	
PBN	Performance Based Navigation	Aviation navigation concept
PNT	Position Navigation and Timing	
PPP	Precise Point Positioning	
QZSS	Quasi-Zenith Satellite System	
R&D	Research & Development	
R&I	Research & Innovation	
RAIM	Receiver Autonomous Integrity Monitor	
RNP	Required Navigation Performance	
RNW	Radio Navigational Warnings	
RPAS	Remotely Piloted Air Systems	
RPASP	Remotely Piloted Aircraft Systems Panel	
RTCM	Radio Technical Commission For Maritime Services	
RTK	Real Time Kinematics	
RW	Restricted Waters	
SARP	Standards And Recommended Practice	
SAE	Society of Automotive Engineers	
SBAS	Space Based Augmentation System	
SEASOLAS	SEASOLAS – Maritime Safety Service based on EGNOS Version 3	European Commission Funded Project Tender ID 534/PP/GRO/RCH/16/9261
SISA	Signal in Space Accuracy	
SoL	Safety of Life	
SOLAS	Safety of Life at Sea	Referring to International Convention for the Safety of Life at Sea (SOLAS), 1974
SSR	Secondary Surveillance Radar	
STCW	Standards of Training Certification and Watch-keeping	
TCAS	Traffic Collision Avoidance System	
TDA	Temporary Danger Areas	
TRL	Technology Readiness Level	
TTA	Time to Alert	

Acronym	Term	Comments
UAM	Urban Air mobility	
UAS	Uncrewed Aerial System	
UK EEZ	UK Economic Exclusive Zone	
UKHO	UK Hydrography Office	
UPM	User Position Monitoring	
URA	User Range Accuracy	
V&V	Verification and Validation	
VAIM	Vessel Autonomous Integrity Monitor	INSPIRe integrity concept
VDE-SAT	Satellite downlink for VDES	
VDE-TER	Terrestrial downlink for VDES	
VDES	VHF Data Exchange Service	
VLOS	Visual line Of Sight	
VTOL	Vertical Take Off and Landing	
WAAS	Wide Area Augmentation System	
WWRNS	Worldwide Radio Navigation System	

3 SUMMARY OF INSPIRE'S RESULTS

3.1 INSPIRe Integrity Architecture

INSPIRe's integrity concepts monitor, and in some cases improve, the integrity of a mariner's GNSS-derived positioning solution.

These integrity concepts can be integrated into a GNSS-based integrity architecture consisting of both user-level algorithms and system-level integrity components. A concept for this architecture, utilising the components considered in INSPIRe, is illustrated in Figure 1.

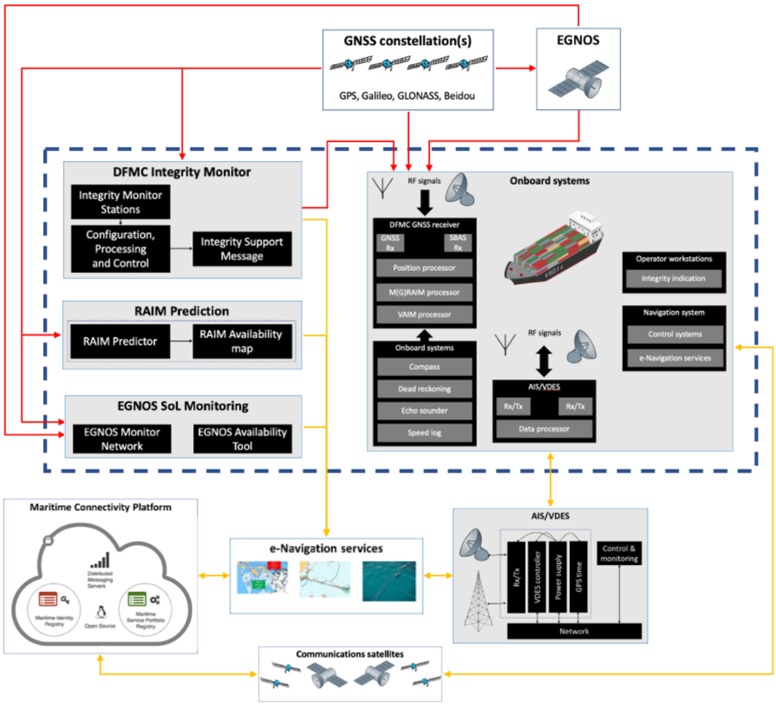

Figure 1 – Concept GNSS-based integrity architecture considered by INSPIRe

3.1.1 User Level Algorithms

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

- **Maritime General RAIM (MG-RAIM)** – a simplified fault detection user-level algorithm which provides integrity monitoring using a geometry screening approach (refer to D2.1 [5] and D3.1 [6]).
- **Maritime RAIM (M-RAIM)** – a fault detection and exclusion user-level algorithm based on the aviation A-RAIM approach to provide integrity by calculating a protection level (refer to D3.1 [6]).
- **Vessel Autonomous Integrity Monitoring (VAIM)** – a user-level algorithm which uses dead reckoning (DR) inputs to provide integrity monitoring by checking coherence of the integrity of positioning solutions (refer to D4.1 [6]).

These algorithms are evaluated in various configurations; using single frequency GPS L1 and DFMC GNSS, and with and without augmentation using SBAS.

The project also developed a proof-of-concept of **peer-to-peer data sharing** that uses ship-to-ship communications and ranging sensors to check the coherence of positioning information between vessels and improve integrity performance, through crowdsourcing (refer to D8.1 [11]).

3.1.2 System Level Integrity Concepts

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 developed:

- **UK dual frequency, multi-constellation (DFMC) Integrity Monitor (DIM)** – a system-level integrity monitoring concept which monitors the integrity of the satellites in view using a UK based monitoring network. The DIM provides an integrity status of GNSS satellites, which can be used to disseminate integrity information to users; either through Maritime Safety Information (MSI) radio navigation warnings and/or as a live message to users using e-Navigation (refer to D7.1 [10]).
- **UK EGNOS Monitor** – a system-level integrity monitoring concept which monitors the outputs of EGNOS to provide means for a UK Competent Authority to assure a Safety of Life (SoL) guarantee for EGNOS augmentation data within the UK Exclusive Economic Zone (EEZ). This concept includes an availability tool which provides a coverage estimate for the area covered by the monitor (refer to D5.1 [8]).

In addition, **opportunistic sources** of data for DFMC integrity monitoring were examined. Improvements in error characterisation were investigated to improve the error bounding, and thus integrity performance, of integrity monitoring algorithms at the system-level (refer to D8.1[11]).

3.1.3 Supporting tools

INSPIRe developed a **RAIM Prediction Tool**. This is a software tool which forecasts the integrity performance for a user utilising the MG-RAIM and/or M-RAIM algorithms based on satellite visibility and geometry, enabling users to predict the performance of their positioning solution over a mission (refer to D6.1 [9]). This is analogous to the AUGUR RAIM prediction tool/service provided by EUROCONTROL in the aviation sector.

3.2 INSPIRe Requirements Set

INSPIRe developed a set of requirements (refer to D1.1[2]) to define operational, functional, non-functional and performance requirements for a GNSS integrity architecture for maritime at the user-level. These requirements are derived from the user needs and requirements identified by MarRINav, and are further developed within INSPIRe both by assembling a consolidated requirement set and through engaging with maritime and PNT stakeholder communities.

The requirements are designed to be solution agnostic to provide a requirement set for components which can integrated as an architecture, and to lead to the development of solutions which meet the needs of the maritime sector.

These requirements consisted of:

- A high-level Concept of Operations (ConOps) that provides the operational requirements for the use of a maritime GNSS integrity architecture;
- Functional requirements define the practical objectives for the integrity architecture;
- Non-functional requirements cover compatibility and integration with other systems;
- Performance requirements identify the required level of navigational performance per voyage phase; and

- Future requirements represent future needs of the maritime sector, considering uses cases such as autonomous operations, increased safety needs and other future mission critical use cases.

The requirement set is applied to, and validated for, each of the components of INSPIRe's integrity architecture. These results are summarised in section 3.3.

An overview of these requirements is provided in the remainder of this section.

3.2.1 Concept of Operations

The ConOps defines integrity based on the IMO definition [16]:

"The ability to provide users with warnings within a specified time when the system should not be used for navigation due to detected faults or an inability to detect faulted conditions"

It sets out the need for an integrity architecture to monitor and alert the user of threats and faults when they are detected, or when the system has an inability to detect faulty conditions according to specified performance bands.

It also sets out the geographical limits and high level requirements for the architecture of a system-level monitoring system, to ensure warnings are disseminated to users within a specified time when an alert is triggered.

3.2.2 Functional and non-functional requirements

In summary, these requirements specify:

- fault detection and mitigation requirements;
- safety and redundancy requirements;
- configurability requirements;
- integrity alerting using a red/amber/green indication;
- onboard interface requirements using the NMEA 0183 $GFA sentence; and
- performance testing requirements.

3.2.3 Performance requirements

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). These requirements are amended to include a risk of false alarm to introduce reliability targets as a first step for introducing integrity into the requirements. This enables the performance of the user-level integrity solutions to be evaluated against the extant navigation performance requirements. Table 1 provides a summary of these performance bands.

Table 1 - Navigation Performance Requirement Bands set out by INSPIRe

Performance Band	Navigation Performance Requirements	Example Use Cases
Performance Requirements based on A.1046(27)		
Ocean Phase	• Horizontal Accuracy (95%) 100m • Availability >99.8% • Continuity >99.97% per 15 minutes • Time to Alarm as soon as practicable by MSI • Risk of False Alarm 1e-5 per epoch	General navigation: Ocean Phase
Coastal Phase	• Horizontal Accuracy (95%) 10m • Availability >99.8% • Continuity >99.97% per 15 minutes • Time to Alarm 10 seconds • Risk of False Alarm 1e-5 per epoch	General navigation: Coastal Phase

Performance Band	Navigation Performance Requirements	Example Use Cases
HEA and Restricted Water Phase	• Horizontal Accuracy (95%) 10m • Availability >99.8% • Continuity >99.97% per 15 minutes • Time to Alarm 10 seconds • Risk of False Alarm 1e-5 per epoch	General navigation: HEA and RW phases

3.2.4 Future requirements

A set of future requirements are set out to represent the future needs of the maritime sector.

The future functional requirements consider:

- provision of quantised numerical integrity information;
- identifying cause of integrity failure; and
- interference detection.

Future performance requirement bands are based on IMO Resolution A.915(22) [16] and the EUSPA survey on requirements for autonomous navigation [17]. These requirements are summarised in Table 2. It is worth noting that these requirements represent a significant evolution on the extant ones, not only in terms the level of performance they specify, but in how they parameterise integrity monitoring performance in terms of integrity risk.

Table 2 – Future Navigation Performance Requirement Bands set out by INSPIRe

Performance Band	Navigation Performance Requirements	Example Use Cases
Future Performance Requirements based on A.915(22) and EUSPA survey		
Ocean Phase	• Horizontal Accuracy (95%) 10m • Availability >99.8% • Continuity >99.97% per 15 minutes • Time to Alarm 10 seconds • Integrity Risk 1e-5 per 15 minutes at HAL of 25m	Future maritime operations in the Ocean Phase derived from A.915 requirements and the MarRINav study
Coastal Phase	• Horizontal Accuracy (95%) 10m • Availability >99.8% • Continuity >99.97% per 15 minutes • Time to Alarm <10 seconds • Integrity Risk 1e-5 per 15 minutes at HAL of 25m	Future maritime operations in the Coastal Phase derived from A.915 requirements and the MarRINav study
HEA and Restricted Water Phase	• Horizontal Accuracy (95%) 10m • Availability >99.8% • Continuity >99.97% per 15 minutes • Time to Alarm <10 seconds • Integrity Risk 1e-5 per 15 minutes at HAL of 25m	Future maritime operations in the HEA and Restricted Water Phase derived from A.915 requirements and the MarRINav study
Port Phase	• Horizontal Accuracy (95%) 1m • Availability >99.8% • Continuity >99.97% per 15 minutes • Time to Alarm <10 seconds • Integrity Risk 1e-5 per 15 minutes at HAL of 2.5m	Future maritime operations in the Port Phase derived from A.915 requirements and the MarRINav study
Autonomous Ocean Phase	• Horizontal Accuracy (95%) 15m • Availability >99.8% • Continuity Risk <1.1e-5 per 15 minutes • Time to Alarm <8 seconds • Integrity Risk 1.1e-6 per 15 minutes at HAL of 28m	Future maritime autonomous operations in the Ocean Phase based on EUSPA survey analysis
Autonomous Coastal Phase	• Horizontal Accuracy (95%) 5m • Availability >99.8% • Continuity Risk <1.1e-6 per 15 minutes • Time to Alarm <6 seconds	Future maritime autonomous operations in the Coastal Phase based on EUSPA survey analysis

Performance Band	Navigation Performance Requirements	Example Use Cases
	• Integrity Risk 1.1e-7 per 15 minutes at HAL of 12.5m	

3.3 Performance of the integrity concepts

Each of the integrity concepts has been evaluated against INSPIRe's requirement set to assess its compliance, covering functionality, performance, compatibility and integrability. D1.1[2] presents the complete validation results against core and future requirements sets and provides a detailed discussion of these results. A summary of the key validation results is presented here.

3.3.1 User-level algorithms

The detection capabilities and performance achieved by the user-level algorithms are summarised in Table 3 and Table 4. The performance results were evaluated for various configurations of GNSS receiver, including GPS L1, DFMC, and with SBAS augmentation.

Some configurations were not evaluated, due to limitations in algorithm capability, data availability or solution maturity in the case of the most novel elements of the INSPIRe project. These cases are listed as "not evaluated".

Table 3 - Detection capabilities of the user-level algorithms

	GNSS Threats				
Integrity Concept	**Satellite ramp errors**	**Satellite bias errors**	**Local multipath**	**Multiple satellite failures**	**Spoofing/ jamming**
MG-RAIM	●	●	●	●	Not evaluated
M-RAIM	●	●	●	●	Not evaluated
VAIM	●	●	●	●	Not evaluated
P2P	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated

Table 4 - Performance results for the user-level algorithms

		Performance Band Results			
Integrity Concept	**Configuration**	**Ocean Phase (refer to Table 1)**	**Coastal Phase** (refer to **Table 1**)	**HEA and RW Phase** (refer to **Table 1**)	**Port Phase** (refer to **Table 2**)
MG-RAIM	GPS L1				
	GPS L1 + SBAS				
	DFMC				
	DFMC + SBAS				
	DFMC + DIM	Not evaluated	Not evaluated	Not evaluated	Not evaluated
M-RAIM	GPS L1	Not evaluated	Not evaluated	Not evaluated	Not evaluated
	GPS L1 + SBAS	Not evaluated	Not evaluated	Not evaluated	Not evaluated
	DFMC				
	DFMC + SBAS				
	DFMC + DIM	Not evaluated	Not evaluated	Not evaluated	Not evaluated
VAIM	+ MG-RAIM	Not evaluated	Not evaluated	Not evaluated	Not evaluated
	+ M-RAIM	Not evaluated	Not evaluated	Not evaluated	Not evaluated
P2P	n/a	Not evaluated	Not evaluated	Not evaluated	Not evaluated

3.3.1.1 MG-RAIM and M-RAIM

The MG-RAIM and M-RAIM user-level algorithms were tested in accordance with the INSPIRe Test Scenario Specification [3] and Threats and Faults List Specification [4], covering single and multiple satellite system faults including ramp and bias errors, signal corruption and bad ephemeris data, Ionospheric faults resulting in an elevated Ionospheric delay, and local user-level faults such as multi-path. Both approaches were shown to successfully detect all threats and faults within scope and issue an integrity alert, although their performances differed.

- For MG-RAIM in the GPS L1 configuration the performance required for the Ocean phase is achieved.
- For MG-RAIM in the GPS-L1/SBAS, DFMC and DFMC/SBAS configurations the performance requirements up to the Coastal and HEA and Restricted Water phases are achieved, but the performance required for the Port phase is not achieved.
- For M-RAIM in the DFMC and DFMC/SBAS configurations the performance requirements up to the Coastal and HEA and Restricted Water phases are achieved, but the performance required for the Port phase is not achieved.

All testing was based on simulated errors injected into fault-free real-world data sets and simulated testing taking a Monte-Carlo approach. These performance results were treated as indicative and primarily used for *comparative evaluation* of the approaches developed. This is for two reasons, firstly the volume of data against which the solutions were tested was not sufficient to represent the gamut of maritime environments, receiver configurations, or to highlight the statistical properties of the approaches towards the tails of their distributions. Secondly, the performance evaluation was contingent on the error model, which describes the statistical likelihoods and properties of the various threats and faults considered; changing this model would directly change the level of performance observed. For the maritime domain there is currently no agreed, validated, error model; a model was assumed based on the aviation case and on previous work on error characterisation carried out by members of the project consortium, however this would need to be a standardised and agreed error model for the maritime domain were these results to be indicative of an absolute performance level. Developing an appropriate and representative error model, and collecting the data necessary for error characterisation, is seen as a priority next-step by the Project. In Section 4 we discuss this in greater detail.

3.3.1.2 VAIM

The VAIM algorithm builds upon M-RAIM to include additional PNT sources from multi-system shipborne receivers, aligned to the IMO's approach. The purpose of this is to improve integrity monitoring performance and resilience by considering the full gamut of PNT sources that may be part of a vessel's PNT system of systems. The VAIM approach developed and implemented an integrity monitoring architecture that is agnostic to the types of PNT source used by the vessel – meaning that it is compatible and integrable with all PNT sources – although for the purpose of testing the project considered the integration of dead reckoning with DFMC GNSS + SBAS.

This was shown to successfully meet functional requirements and to detect the threats and faults in scope. However, performance evaluation was not achieved. Two challenges prevented this: the more complex simulation environment (or representative data sets) required to describe inertial measurements coupled with simultaneous GNSS position measurements; and the need for a representative characterisation of the errors and statistical properties associated with the inertial measurements. Further work is required to analyse the performance benefits VAIM might provide.

3.3.1.3 Peer-to-peer communication

Part of the project's investigation of next-generation improvement to integrity monitoring included considering the role of signals of opportunities and peer-to-peer (ship-to-ship) sharing of PNT and integrity information. A solution looking at this test case was implemented and tested in a simulation environment, showing core functionally and demonstrating a potential to augment integrity monitoring and potentially highlight threats, such as spoofing, that are out of scope of the M-RAIM, MG-RAIM and VAIM methods.

The project's scope did not extend to integrating this with the tested user-level solution to provide comparative performance metrics, however the functional validation and qualitative benefits provide strong reason to develop this further in subsequent work.

3.3.2 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. Table 5 identifies the detection capabilities of the system-level integrity concepts, where detection is relevant.

Table 5 - Detection capabilities of the system-level integrity concepts

	GNSS Threats				
Integrity Concept	Satellite ramp errors	Satellite bias errors	Local multipath	Multiple satellite failures	Spoofing/ jamming
DFMC Integrity Monitor	●	●	Not relevant	●	Not evaluated
EGNOS Monitor	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
RAIM Prediction Tool	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant

3.3.2.1 DFMC Integrity Monitor

The DFMC Integrity Monitor (DIM) is shown to successfully detect all system-level threats and faults within the Threats and Faults List Specification [4], and to correctly generate integrity flags. This demonstrates the potential of the DIM to generate an alert which may be disseminated to users.

The user-level processing of the DIM integrity message was out of scope of INSPIRe and therefore the performance benefit of the DIM to the user is yet to be established. This will require user-level processing to be developed and dissemination methods to be implemented. These activities are further discussed in section 6.3.

3.3.2.2 EGNOS Monitor

The EGNOS Monitor sets out a monitoring approach using a User Position Monitoring (UPM) algorithm, based on the approach developed for the WAAS augmentation network. This approach 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, but validation will be required during implementation. GNSS threat detection is not the role of the EGNOS Monitor hence the detection capability functionality is not relevant.

The activities required to implement the EGNOS Monitor are outlined in section 6.2.

3.3.2.3 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 outlined in Section 6.1.

3.4 Maturity of the integrity concepts

This section identifies the current maturity of the integrity concepts based on the development activities completed in INSPIRe. The maturity is estimated by the project using the European Space Agency (ESA) definitions of Technology Readiness Level [13].

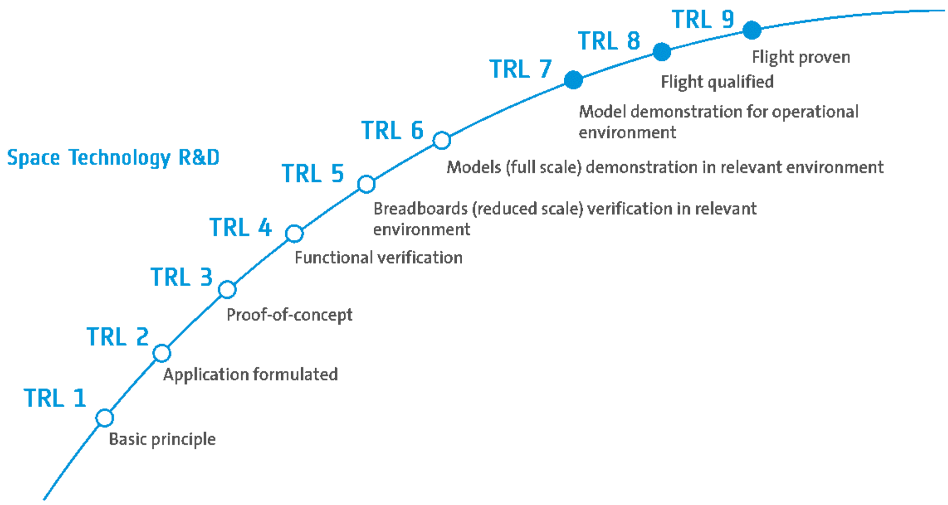

Figure 2 – European Space Agency TRLs. Source: ESA

Table 6 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 [2].

Table 6 - Technology Readiness Levels of integrity concepts developed in INPSIRe

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 inputs 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
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

Section 4 of this report discusses the activities required to further mature the integrity concepts to enable them to be implemented in an operational environment. Further sections of this report then discuss the work required to implement the integrity concepts, through standardisation, system-level implementation and adoption by non-regulated users.

3.5 Benefits of the INSPIRe integrity architecture

High-Level Cost Benefit Analysis D9.1 [12] considered the benefits of implementing INSPIRe's integrity architecture by analysing 13 specific use cases in the maritime sector.

Each use case has been considered against a localised scenario to identify the socio-economic costs of a navigation failure within the North Sea or Orkney regions. The analysis then identifies the benefits that alerts generated by INSPIRe's integrity architecture can provide by enabling the mariner to mitigate navigational loss scenarios. The results are extrapolated from the localised scale to a national scale to identify the potential benefits across the UK EEZ.

The results identify potential benefits of £2.2bn across the UK EEZ over a 20-year period based on the use cases analysed in the study. The most significant benefits identified are reducing emergency activities in fisheries, protection of Marine Protection Areas from bottom-trawlers, and increasing benefits as operations of Maritime Autonomous Service Ships are introduced.

If the performance of INSPIRe's integrity architecture were to be improved to provide integrity monitoring beyond the Coastal performance band, the analysis indicates that up to £2.6bn of potential integrity benefits could realised in the North Sea and Orkney regions across the use cases considered in this study. This could be significantly more when scaled to the UK EEZ.

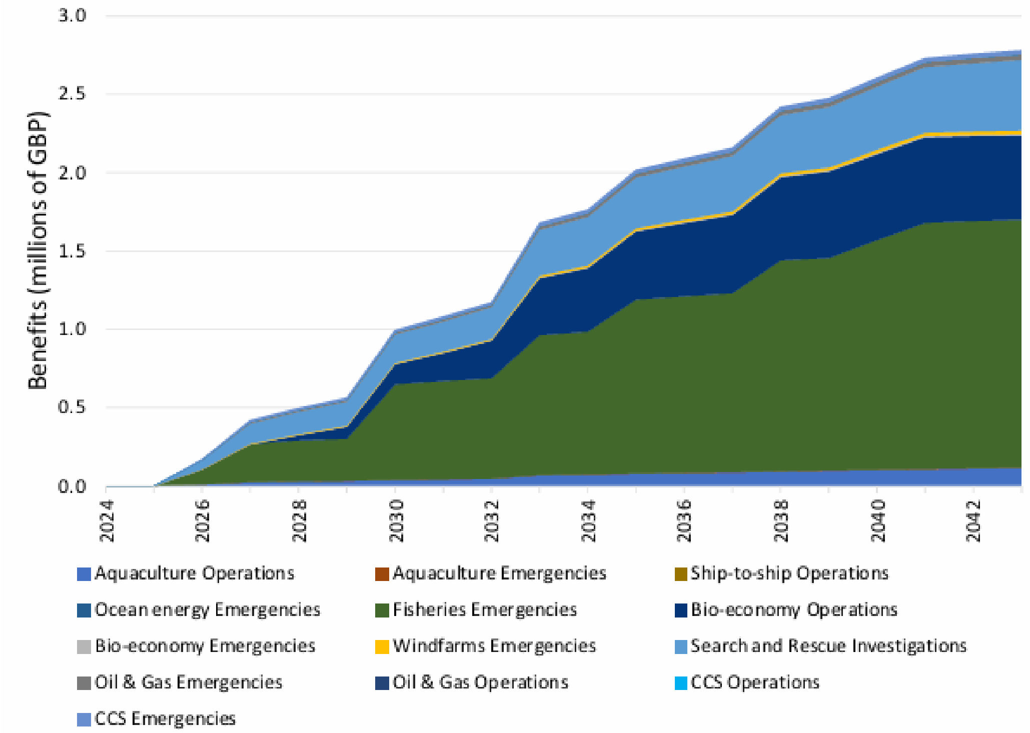

Figure 3 - Annual benefits from INSPIRe mitigation of integrity failure events (geographically modelled scenarios)

4 DEVELOPING THE USER LEVEL INTEGRITY CONCEPTS

4.1 Maturing the user-level integrity concepts

Sections 3.3 and 3.4 provided a summary of the current level of maturity and performance of the user-level algorithms. This section identifies activities required to advance the TRL of the user level algorithms to operational maturity.

Eight key activities are identified:

- Characterising local fault conditions in the maritime environment
- Integrating VAIM with other DR sensors
- Integrating peer-to-peer methods with user-level receivers
- Technical advancements of the user-level algorithms
- Integrating the DIM message with user-level receivers
- Performance validation of user-level algorithms in the maritime environment
- Peer review and validation of the integrity concepts
- Developing user-level test standards

4.1.1 Characterising local fault conditions in the maritime environment

Local error models are key to characterising performance of GNSS in the maritime environment, to consider local effects such as NLOS and multipath errors. Specifically, they are required to:

- characterise the local environment to enable representative performance testing of GNSS algorithms and receivers;
- provide a configuration input to M-RAIM to set the error bounds used for calculating the protection level; and
- provide a configuration input for RAIM prediction of M-RAIM performance.

Note the following integrity concepts are designed to not require inputs of maritime local error models, and thus do not depend on this activity:

- MG-RAIM is designed specifically to not require local error models and thus simplifies the implementation of this integrity concept;
- RAIM prediction of MG-RAIM performance, given that error models are not a prerequisite for MG-RAIM; and
- system-level solutions where the user's local environment is out of scope of the system.

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 a number of factors including:

- quality of user receivers;
- placement of receiver installations on vessels;
- increased uncertainty in signals from satellites with low elevation angle;
- limited satellite visibility due to ground level receivers;
- reflections from ground and sea; and
- obstruction from port infrastructure and other vessels.

This is in contrast to aviation where the effects of the local environment is far less significant due to the relatively unobstructed environment and increased satellite visibility.

A conservative error model will provide the user with greater availability and a low integrity risk of missed fault detection but less accuracy performance, whereas a less conservative error model will provide greater accuracy performance at the cost of lower availability and higher integrity risk.

Where local error models are required INSPIRe has used the results of SEASOLAS to provide an input error model. SEASOLAS was a study completed in 2018 [20] which established an error model based on collecting GNSS data from sea trials within various maritime environments. However, this error model is generalised to account for the varied nature of the maritime environment to provide a single error model without compromising integrity risk. This results in an error model which is likely conservative in many maritime scenarios where there is likely to be limited disruption from local error effects (such as in the Ocean phase), and thus this is reflected in INSPIRe's performance results of the M-RAIM algorithm with a reduced accuracy performance.

This activity therefore recommends the need for further long-term trials across multiple vessels to improve knowledge of local errors in the maritime environment. This data will enable errors to be better characterised such that representative error models can be established for varying user environments. For example, varying error models per voyage phase, or considering varying receiver installation qualities.

This will enable a better configuration of error models in user-level algorithms such that higher performance requirements can be met without increasing the risk of hazardously misleading information. It will also support better user-level testing, with an improved understanding of the likely conditions that a maritime receiver will encounter.

As part of these proposed trials, it is noted the M-RAIM algorithm provides a facility to implement a testing platform which enables local error models to be configured and therefore can support validation of error models.

4.1.2 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.

VAIM therefore enables a relatively low cost integration between GNSS and existing DR sensors to provide integrity monitoring without new sensor installations. It also provides opportunity to reduce the workload of the mariner by enabling VAIM to check coherence of the GNSS and DR sensor outputs, instead of relying on the mariner to check coherence themselves.

Further expansion of the VAIM concept is therefore recommended to further develop and evaluate sensor integration. This will require long term and coordinated data collection of both GNSS and DR navigation systems to characterise errors across multiple PNT inputs to provide a realistic test environment and enable performance testing. Testing will be required across multiple vessels and different DR sensors to develop a VAIM solution which is suitable to implement across a wide range of vessels.

4.1.3 Integrating peer-to-peer 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 [11] 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.

4.1.4 Technical advancements of the user-level algorithms

Within D8.1 [9] 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 [9]:

- 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.

4.1.5 Integrating the DIM message with user-level receivers

As discussed in section 3.3.2.1 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.

Section 6.3.5.2 discusses the opportunity to exploit existing e-Navigation infrastructure to disseminate the DIM message to a receiver, and hence use this as a demonstrator for user-level processing of the DIM message. This demonstrator will enable the performance contribution of the DIM message to be evaluated at the user-level, and also to compare the benefits of the DIM in complement to, or in contrast to, extant systems such as SBAS.

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.

4.1.6 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.

For example, variations in environment and receiver quality lead to fault conditions such as noise/interference, multipath and NLOS. These faults will occur with varying significance due to external factors and across mission phases as vessels interact with different environments.

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

- **Software simulation using maritime GNSS receiver data.** This activity requires collecting data from vessel receivers across various mission phases and vessel types. This data can then provide a testing platform which will enable user-level algorithms to be evaluated under real-world conditions without the expense and long time frames of long-term algorithm deployment.

- **Degraded scenario testing.** User-level algorithms should be evaluated under controlled degraded scenarios to understand their functionality, performance and limitations when subject to extreme fault conditions, such as exposure to noise, interference, jamming, spoofing and meaconing faults, extreme local fault conditions, or due to poor receiver siting.

- **Long-term deployment on vessels.** This activity aims to evaluate user-level performance in real-world conditions over a long term timeframe, to validate that integrity risk, availability and continuity requirements continue to be met in all voyage phases.
- **Performance validation of VAIM**. This is considered as a separate activity due to the complex nature of testing fault scenarios from the two sources of data (GNSS and DR). A performance testing regime for various DR sensor integrations needs to be established, considering fault scenarios which are both independent and dependent between the navigational inputs.

These testing regimes will enable the performance of the user-level algorithms to be characterised based on real data, including in both fault free and degraded scenarios. This will enable the user-level algorithms to be fully validated against the performance requirements and hence enable the integrity risk, availability and continuity of the user-level algorithms to be calculated at various levels of required accuracy performance.

The performance results will support both the assurance of the algorithms (for example to support developing standards), and identifying the level of integrity performance that can be achieved by the user's GNSS receiver.

4.1.7 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.

Further peer review of the integrity concepts from external stakeholders is strongly encouraged throughout future development and validation stages. This will ensure continued scrutiny to ensure the design and approaches applied are robust, and any vulnerabilities or shortfalls in design or validation processes are addressed throughout the development process. The peer review process will also provide supporting evidence to demonstrate that a robust process has been followed in design and validation when assuring the integrity concepts.

The current status of peer review of the integrity concepts is summarised in the following sections.

4.1.7.1 Peer review of the user-level integrity concepts

Prior to INSPIRe, the MG-RAIM and M-RAIM integrity concepts were subject to peer review in the early concept phase by Stanford University, as referenced in D3b GNSS Integrity of the MarRINav study. The continued development and validation of the MG-RAIM and M-RAIM algorithms is presented within the D2.1[3] and D3.1[4] reports.

The VAIM concept provides a newly established integrity concept which has been reviewed within the INSPIRe consortium. Functional descriptions and validation results are presented within the D4.1[5] report.

The peer-to-peer communication integrity concept also provides a newly established integrity concept. A functional description of the peer-to-peer integrity concept is presented within D8.1[9] report.

Both in their current level of development and as they are further developed, it is recommended to share these algorithms with GNSS experts, receiver manufacturers, IEC technical committees and amongst the maritime community to enable a wider review of these integrity concepts and to ensure the relevant standards organisations are engaged in the development of the algorithms.

4.1.7.2 Peer review of the system-level integrity concepts

For both the DIM and EGNOS Monitor system-level integrity concepts, these are both early stage concepts which have been subject to review within the INSPIRe consortium.

A DIM for a UK geographic area is a newly proposed integrity concept within INSPIRe. The results of the technical development and evaluation of the DIM are presented in D7.1[8].

As part of the proving and implementation of the DIM it is recommended that continued peer review is maintained throughout the development of both the user-level and system-level aspects of the DIM. This process should include GNSS experts, user-level representation (receiver manufacturers from both maritime and other relevant sectors) and the responsible UK Authority for adopting and maintaining the DIM. These review activities will support the technical justification of the safety and performance of the system by demonstrating a robust design process.

The EGNOS Monitor is based on the UPM implemented in WAAS, thus there is an existing degree of scrutiny applied to this concept when it was established in the WAAS service area. The UPM concept is yet to be established in a UK geography and the technical considerations for this are described within D5.1[6].

A continued peer review process for the EGNOS monitor is recommended throughout its development and implementation to continue to support in identifying the risks that any UK Authority will become responsible for when implementing and adopting the EGNOS Monitor, and demonstrate a robust development process to enable the EGNOS Monitor to assure the use of EGNOS safety-of-life services. Relevant stakeholders are recommended to include GNSS technical experts from ESSP (as the EGNOS service provider), the proposed service provider of the DIM in the UK and the relevant UK Authority.

4.1.8 Developing user-level test standards

Throughout INSPIRe the system engineering process and subsequent validation has enabled the performance of the user-level algorithms to be compared against each other using a common validation methodology. As discussed within D1.1[2], the performance of the integrity concepts have been evaluated by injecting simulated errors over fault-free GNSS receiver data.

However, this has a shortfall of not necessarily representing a real-world GNSS environment in maritime, and without thorough definition of the test environment, creates opportunity for interpretation and variability in the testing conditions. To enable a consistent application of GNSS integrity in receivers and vessels it is therefore recommended to define the testing environment such that it represents the maritime environment (including considerations of receiver placement and installation quality, and local effects such as NLOS and multipath). It is also important to include a degree of variability to ensure that algorithms are not tuned to the specific test environment as opposed to real-world conditions.

This activity is coupled with the activities recommend in sections 4.1.1 and 4.1.6. This is because to develop representative test conditions requires prerequisite knowledge of the local maritime environment. The performance validation activities of the user-level algorithms also provide an opportunity to validate test conditions to ensure that they are representative and enable them to be formalised as industry-wide test standards for user-level conditions.

4.2 Improving the GNSS Integrity Architecture

This section provides a brief summary of opportunities which may be considered to improve performance of the integrity architecture.

INSPIRe's conceptual integrity architecture is presented in Figure 1, and repeated here for ease of reference (refer to Figure 4). This architecture is derived from a wider resilient PNT architecture proposed by MarRINav [21], illustrated in Figure 5.

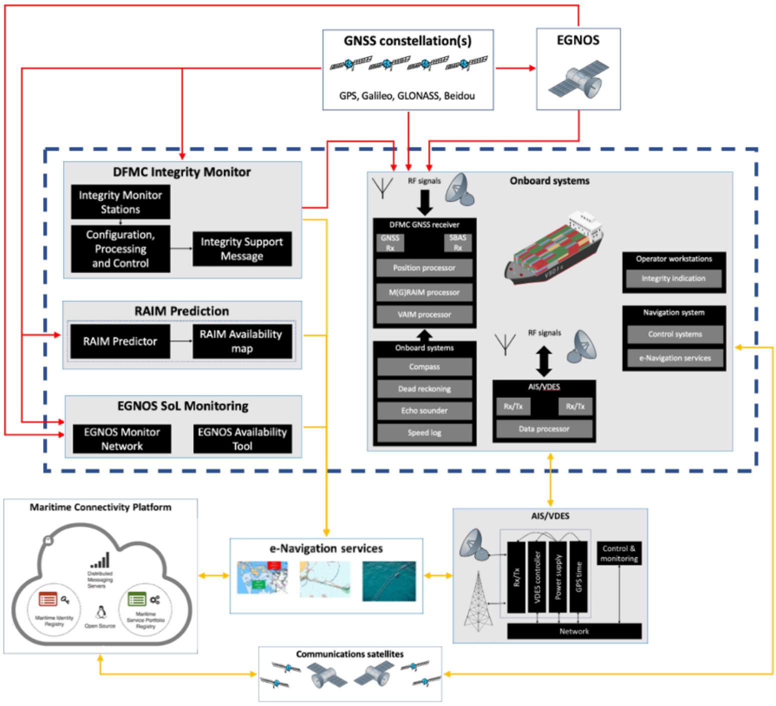

Figure 4 – Future GNSS Integrity architecture considered by INSPIRe

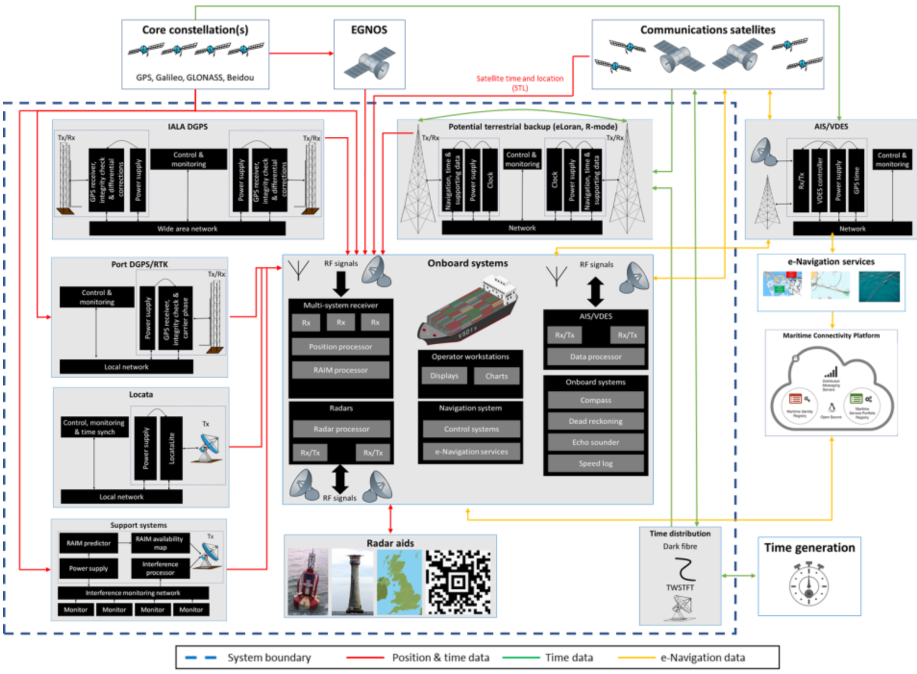

Figure 5 – MarRINav conceptual architecture for a resilient PNT system-of-systems

The results of INSPIRe demonstrate that the integrity concepts can meet performance bands up to the requirements for Coastal navigation, however the results recognise several key limitations of the integrity concepts, namely:

- spoofing and meaconing threats are not directly addressed by the user-level integrity concepts, nor is detection capability of these threats checked within INSPIRe;

- integrity concepts do not provide resilience in the case of GNSS service loss or GNSS integrity loss – the mariner is only alerted of the failure and thus must navigate by alternative means;
- performance bands with higher demands than Coastal phase are not met; and
- no integrity of timing information is provided.

Although not directly considered by INSPIRe there are emerging technologies which may provide opportunities to address these limitations by expanding the integrity architecture.

MarRINav recognises a number of these technologies, for example terrestrial backup systems (e-Loran, VDES R-Mode), DGPS/RTK, radar aids and time distribution networks. Further technologies are also emerging in the PNT sector such as 5G positioning, LEO-PNT, onboard Radio Frequency interference monitoring, PPP, relative positioning and encrypted GNSS, which each may provide benefits to a wider PNT architecture.

INSPIRe has not specifically considered these technologies so no judgement of the benefits of these technologies it provided here. However, it is recommended that alternative integrity concepts are also considered alongside INSPIRe's integrity architecture to address its limitations.

5 DEVELOPING STANDARDS FOR MARITIME NAVIGATION

This section explores how INSPIRe's results can support the development of maritime navigation standards. The proposed activities aim to standardise and widen the adoption of integrity to improve safety and enable future use cases in maritime. Specific inputs from INSPIRe, relevant stakeholders and indicative timelines for these activities are identified.

This section also considers the standards required to implement INSPIRe's system-level integrity concepts in the UK and to enable their exploitation by users.

5.1 Current Maritime Navigation Standards

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.

The IMO sets out the required levels of navigation performance for a worldwide radio navigation system within IMO Resolution A.1046(27), adopted in November 2011. This provides minimum requirements for providing a general navigation service for vessels (i.e. the performance that a GNSS system must provide to a maritime user). The A.1046(27) requirements are split into performance bands for vessels operating under general navigation in ocean waters, harbour entrances, harbour approaches and coastal waters operational phases.

A.915(22), adopted by the IMO in November 2001, proposes a set of system and user requirements for a "future GNSS". This identifies general, operational, institutional and transitional requirements including user performance requirements for various maritime use cases, however A.915(22) is not adopted as a formal maritime standard.

For general navigation the IMO sets out resolutions that state the requirements for shipborne equipment to provide a means for vessels to satisfy the requirements set out by SOLAS for general navigation. The relevant resolutions for GNSS shipborne equipment are:

- MSC.112(73) on GPS;
- MSC.113(73) on GLONASS;
- MSC.114(73) on DGPS and DGLONASS;
- MSC.115(73) on Combined GPS & GLONASS;
- MSC.233(82) on Galileo;
- MSC.379(93) on BeiDou;
- MSC.401(95) & MSC.432(98) on Multi System;
- MSC.449(99) on IRNSS; and
- MSC.480(102) on QZSS.

Further to the IMO resolutions the IEC defines specific receiver test specifications which seek to test the minimum functional and performance requirements to enable GNSS receiver equipment to be certified for maritime applications:

- IEC 61108-1:2003 on GPS;
- IEC 61108-2:1998 on GLONASS;
- IEC 61108-3:2010 on Galileo;
- IEC 61108-4:2004 on DGPS & DGLONASS;
- IEC 61108-5:2020 on BeiDou;
- IEC 61108-6:2023 on IRNSS; and
- IEC 61108-7:2024 on use of GPS L1 SBAS.

These specifications do not prescribe implementation methods, but provide the minimum requirements, and thus provide standardised testing methodologies, for receiver equipment to meet certification requirements.

5.2 Need for developing the maritime navigation standards

INSPIRe has recognised several key areas in the extant maritime standards which need to be developed to promote a widespread adoption of integrity. These areas were explored within MarRINav and other previous studies as summarised here.

- While IMO A.1046(27) sets out the requirements for world-wide radionavigation systems, from which some maritime requirements can be derived, and IMO A.915(22) sets out future requirements, there is no document that sets out maritime operational requirements as they stand today.
- The requirements specified by A.1046(27) do not fully define what is meant by maritime integrity or how it should be achieved for a GNSS user.
- The standards do not differentiate between user-level and system-level performance nor consider the significance of user-level effects on performance
- The IMO receiver performance standards are inconsistent in their definition of integrity and how they reference RAIM.
- The maritime receiver performance standards have limited consideration for resilience and cascading failure modes in the event of an integrity or availability failure. This is only considered in the Multi-System receiver performance standard.
- The IMO receiver performance standards do not specify requirements for using SBAS, where augmentation is referenced this is largely limited to marine radiobeacon services. While the IEC has developed SBAS standard, there is a need for an IMO instrument to facilitate their use in support of maritime receiver equipment. The IMO has this as a future agenda item, due in 2025/26.

As a result, there is 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. Addressing these areas requires a co-ordinated approach to develop the maritime navigation standards to provide a regulatory framework that meets both the current and future needs of the maritime sector.

5.3 How INSPIRe's integrity concepts can support standards

This section considers each of INSPIRe's outputs against a modified standards framework. This framework proposed to illustrate how INSPIRe's results can support in developing future maritime navigation standards. The framework aims to provide a top-down standards development approach which ensures that user needs are met and there are clear requirements attributed between the user-level and system-levels.

5.3.1 Relevance of the user-level algorithms

INSPIRe's user-level algorithms demonstrate integrity concepts which can be applied onboard a vessel considering the user environment in the maritime sector. Specifically:

- MG-RAIM demonstrates an integrity monitoring concept that can be rapidly deployed in the near term without the need for extensive further validation of the maritime environment;
- M-RAIM demonstrates an integrity monitoring concept based on the well-established aviation A-RAIM approach (by utilising error models to derive a protection level) but adapted for horizonal navigation;
- VAIM demonstrates integrity monitoring by integrating DR navigation systems with GNSS, to illustrate benefits of multi-sensor systems for integrity; and

- the peer-to-peer integrity concept demonstrates the benefits of using AIS and ranging information as signals of opportunity as a potential method of improving integrity performance

These user-level integrity concepts can be implemented within GNSS receivers to provide integrity alerts to the user. However, although the integrity concepts alert the mariner when their GNSS derived position is not safe to use, they do not provide resilience in the event of integrity failures. Thus, the integrity concepts do not supress the need to supplement GNSS with alternative PNT to manage degraded scenarios when a GNSS integrity failure occurs.

5.3.2 Relevance of the system-level integrity concepts and supporting tools

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

The implementation plans for each system-level integrity concept describe the standards required in detail however these standards are also summarised in Table 7 to provide a complete view of the standards development activities required across INSPIRe's integrity architecture.

5.3.3 Potential structure for a future suite of maritime navigation standards

Table 7 explores the relevance of INSPIRe's results in developing the maritime navigation standards. The table is broken down into individual aspects which each represent elements of the maritime navigation standards, to communicate a potential structure for a future suite of maritime navigation standards. The aspects considered are:

- Concept of operations for maritime navigation;
- Navigation requirements for a shipborne navigation system;
- GNSS receiver requirements as part of a shipborne navigation system (including functional, performance and implementation requirements); and
- GNSS receiver test standards.

Also considered are aspects which are not directly related to user-level standards but should be considered throughout the standards development process to develop a complete suite of standards which support INSPIRe's integrity architecture:

- Vessel integration;
- Receiver architecture and processing capability;
- Receiver algorithms;
- User interface with SBAS;
- User interface with DIM;
- Implementation of national infrastructure; and
- RAIM Prediction Tool.

For each aspect a potential standards development approach is outlined, the contributions of INSPIRe towards each aspect is identified, and the responsible entities proposed.

Note the purpose of this section is to identify the potential contributions of INSPIRe and does not necessarily represent a complete standards development process but can be used to guide one.

Table 7 – Proposed aspects relevant to developing maritime standards, and the potential contributions from INSPIRe

Aspect	Description	Standard development activities proposed	Inputs from INSPIRe	Proposed responsible Entity
Concept of Operations	A ConOps is proposed to identify how a PNT system shall be operated based on operational use cases and user needs. The purpose of the ConOps is to enable the system functional and performance requirements for a high performance PNT capability to be defined based on operational use cases.	The ConOps does not represent any specific standard, however an agreed ConOps will support policy and standards development activities and set out an end goal for these activities based on user needs. Two levels of ConOps are proposed: • At an international level a ConOps should define the interoperable operational concept for international maritime operations and navigation relying on PNT • At a national level the ConOps should define a national architecture, and the use cases for it, to define a national level operational concept which is compatible with an international ConOps These ConOps should consider operational use cases for a complete PNT system including resilient PNT capability for use in both typical and degraded maritime scenarios. ConOps must be agreed with relevant maritime users, and users from other sectors where relevant.	INSPIRe has identified a list of high-level use cases for GNSS integrity in the maritime sector. The project has also proposed a set of operational requirements and reference architecture which provide a ConOps for GNSS integrity for positioning and navigation in maritime. These use cases and requirements have undergone a high-level validation with maritime stakeholders. This ConOps can contribute towards a wider resilient PNT architecture. INSPIRe's system-level integrity concepts (EGNOS Monitor, DIM and RAIM Prediction Tool[1]) demonstrate potential components of a national infrastructure, and the user-level integrity concepts demonstrate potential user-level algorithms.	IMO UK Government
User-level Navigation Performance Requirements	User-level navigation performance requirements are proposed to set the required level of performance for a ship's navigation system.	This aspect is equivalent to the PBN requirements applied for aviation, however no such user-level standard for a ship-borne navigation system currently exists in maritime. Although A.1046(27) exists and sets out performance requirements service provision of a worldwide radio navigation system, this standard only sets out system-level requirements (for example for the provision of a GNSS service) and does not provide requirements for the maritime user. A set of ship-borne navigation system requirements based on current and future operational needs will provide a consistent and standardised application of navigation performance for vessels to enable improved safety and future use cases where guaranteed navigation performance is essential. These requirements should also specify requirements for resilience, to maintain performance and recover when an element of the navigation system (such as GNSS-derived	INSPIRe's conceptual integrity architecture is developed to be integrable as a component of a wider resilient PNT architecture, noting that in the event of an integrity failure alternative PNT sources other than GNSS will be required to ensure resilience of the ship's navigation system. INSPIRe has considered performance requirements for a GNSS-based navigation system based on use cases derived from extant standards, MarRINav and through stakeholder engagement with maritime users. These requirements do not directly identify performance requirements for a complete ship-borne PNT but with further validation can be developed to specify the performance allocation of a GNSS-based PNT system as part of a wider onboard PNT system, which is explored in the following aspect.	IMO

[1] The RAIM Prediction Tool may be implemented with an optional shore-based monitoring network. Refer to section 6.1 which describes the implementation of this network.

Aspect	Description	Standard development activities proposed	Inputs from INSPIRe	Proposed responsible Entity
		positioning) is not available or has been subject to an integrity failure. Various studies have been conducted to identify user needs for navigation performance in maritime operational scenarios, significantly the EUSPA User Needs and Requirements study, however these use cases are yet to be consolidated into mandated requirements.		
GNSS Receiver System Requirements – Minimum Performance Requirements for GNSS receivers	GNSS performance requirements are proposed to set the minimum level of performance required for a user's GNSS-based navigation system. The GNSS requirements should be derived from the minimum performance requirements for a complete navigation system, with appropriate performance allocation to the GNSS solution based on the feasible performance of GNSS. These requirements enable the GNSS component of a navigation system to be standardised at the user-level, and therefore receivers can be implemented and graded with a characterised level of performance which is standardised between receiver manufacturers. The GNSS performance requirements are linked with functional requirements and test standards to provide a complete set of receiver requirements.	This aspect is equivalent to A.915(22) which in part sets out recommendations for user requirements for a future GNSS navigation system. However there are currently no formal maritime user-level requirements for a GNSS receiver. GNSS performance requirements can be developed as part of a suite of GNSS system requirements, to set out the performance needs, the need for resilience, and the need for cascading failure modes. Any standard should be solution agnostic to allow flexibility between receiver manufacturer implementations. Multiple performance bands are required to identify appropriate and achievable performance requirements which can be applied across relevant use cases. Specific criteria which must be defined per performance band for a GNSS-based system are: • Availability; • Integrity Risk; • Continuity; • Accuracy (95%); and • Time To Alert. The performance requirements must be coupled with performance testing standards to ensure that the performance requirements are assessed consistently.	INSPIRe has proposed a set of performance requirements based on previous studies and stakeholder engagement across maritime users. These identify potential performance requirements for maritime users to improve the specificity of the extant IMO A.1046(27) and A.915(22) requirements, to enable a wider adoption of integrity for GNSS. INSPIRe's requirements also identify future performance requirements which consider the future needs of mariners in mission critical use cases, for example as degrees of autonomy are adopted. INSPIRe's validation results indicate the level of GNSS performance which is achievable at the user-level when MG-RAIM and M-RAIM algorithms are implemented in a user's receiver, both as standalone single frequency or DFMC solutions, and when integrated with SBAS. The level of validation achieved within INSPIRe is explored in further detail in section 3. Section 4 of this report explores opportunities for maturing INSPIRe's integrity concepts, and further improving the navigation performance of the GNSS-based integrity architecture to meet higher performance requirements.	IEC
GNSS Receiver System Requirements - User-Level Functional and Implementation Requirements	User-level functional requirements set out the minimum requirements for the functionality and implementation a GNSS receiver. These requirements are to be derived from use cases of the GNSS solution in a maritime environment.	The functional requirements should be agnostic to user-level algorithms where possible and developed as part of a suite of GNSS system requirements. The requirements should consider interfaces, functionality, safety, reliability and integration of the GNSS system to enable consistent functionality to be applied across receivers.	INSPIRe has identified a set of functional requirements for a GNSS integrity solution based on maritime use cases and stakeholder engagement. These specify: • fault detection and optional mitigation requirements; • safety and redundancy requirements; • configurability requirements;	IEC

Aspect	Description	Standard development activities proposed	Inputs from INSPIRe	Proposed responsible Entity
		These functional requirements should also consider the user-level requirements for the integration (i.e. the receipt and data processing) with the SBAS Signal in Space as a part of the GNSS. This is further explored in the “User interface with SBAS” aspect.	• integrity alerting using a red/amber/green indication; • interface requirements to other onboard systems using NMEA 0183 $GFA sentence; and • performance testing requirements. A set of future requirements considering future needs of mariners are also specified. These specify: • provision of quantised numerical integrity information; • identifying cause of integrity failure; • interference detection; and • future performance requirements. INSPIRe’s validation results demonstrate the level of functionality and performance achieved by each of the user-level algorithms. This supports to demonstrate the feasibility of the requirements.	
GNSS Receiver System Requirements - Receiver Test Standards	Development of the receiver test standards is proposed to provide a defined and real-world set of conditions. This is to ensure a consistent application of and validation of the performance requirements.	Extant test standards for receivers are provided in the IEC standards described in section 5.1 however they do not provide a consistent methodology for addressing and testing integrity performance of receivers. Test standards for GNSS receivers should be further developed to enable receivers to be graded based on performance provided per mission phase. These test standards should include: • Standardised testing methodologies and test environment for each navigation performance band. • Defined fault probabilities at the local and system levels for all relevant user environments to ensure receivers are validated in realistic test conditions considering the performance of the GNSS constellations, and to ensure that integrity risk can be calculated consistently. • Test cases which represent degraded GNSS environments, including where spoofing, jamming, meaconing, interference and noise faults are present, to determine the performance of GNSS receivers in these scenarios.	INSPIRe has adopted functional testing based on a set of injected fault scenarios, loosely based on the IEC 61108 series of standards. The aim of INSPIRe’s testing methodology is to evaluate the detection capabilities, accuracy and availability performance of the user-level integrity concepts, however it does not necessarily reflect real-world navigation performance. INSPIRe’s testing methodology will need to be developed further to define a robust set of test conditions to enable the integrity performance of user-level algorithms to be fully validated based on representative user environments per voyage phase. As identified in section 4 this will require activities to further understand the maritime environment and further develop specific test activities.	IEC
Vessel integration	The installation of receivers on vessels presents challenges in providing consistent GNSS performance due to the variable	A standard process should be developed to manage receiver placement to ensure that representative error models are implemented for a vessel.	INSPIRe has not specifically investigated the impact of receiver siting on local errors within the project. Error models used throughout the project are based on the SEASOLAS project.	IEC Ship classification societies

Aspect	Description	Standard development activities proposed	Inputs from INSPIRe	Proposed responsible Entity
	nature of vessels, resulting in variations in NLOS and multipath errors, and interference and noise from other onboard systems. These effects vary between vessel types and receiver placements. This impacts the performance of GNSS receivers and the validity of local error models implemented in user-level algorithms and performance prediction tools. If inaccurate local error models are implemented in a user-level algorithm, or receiver performance is tested in an environment which does not reflect the receiver installation, this increases the risk of hazardously misleading information being presented to the mariner. An overly optimistic local error model can invalidate the integrity risk performance of the receiver and an overly conservative local error model can reduce the availability performance of the receiver.	This process represents a need for an equipment integration requirement and/or standard. To implement this process will require receiver manufacturers to develop receivers which maintain performance across vessel installations or can be validated for a specific installation. This may require shipbuilders to validate the placement and installation of receivers as part of the ship building process.	Further investigation is required to determine a methodology for appraising and/or mitigating the impact of receiver placement on local error models. This investigation will need to acknowledge variabilities in local error models for example in the vicinity of other vessels and port infrastructure. The M-RAIM algorithm provides a configurable algorithm which can be configured with an error model, and hence used to test its validity. Likewise, the RAIM Performance Prediction Tool is configurable for error models to enable an accurate performance prediction based on known local error models.	
Receiver architecture and processing capability	This aspect considers the construction and architecture of receiver implementations necessary to implement GNSS navigation systems. Relevant considerations are: • Single frequency or DFMC receiver architecture • SBAS capability and processing • DIM capability and processing • Hardware processing performance • Hardware reliability and redundancy • Implementation of supporting tools	No standards development activities are considered applicable given that receiver design, construction and architecture is the responsibility of receiver manufacturers. The GNSS System Requirements considered in previous aspects are proposed to be solution agnostic when setting out the performance requirements for the GNSS receiver. Thus it becomes the responsibility of the receiver manufacturer to design a receiver with suitable architecture to meet the relevant reliability, availability, maintainability and safety requirements for the performance band(s) applicable to the ship's operation.	INSPIRe's user-level integrity concepts provide demonstrator implementations of user-level algorithms which can be exploited by receiver manufacturers. The algorithms are described within the technical reports for each user-level integrity concept, to provide a technical description which enables implementation by receiver manufacturers. These documents describe the performance of the algorithms when implementing single frequency, DFMC and SBAS inputs, to support receiver manufacturers in determining the required receiver specification for implementing the required level of performance. In INSPIRe, the user-level algorithms are implemented in software test beds and have not explicitly measured the hardware requirements of the algorithms given that the processing	Receiver manufacturers

Aspect	Description	Standard development activities proposed	Inputs from INSPIRe	Proposed responsible Entity
			requirements are implementation specific and depend on configuration and architecture of receivers. However a high-level consideration of hardware requirements is given in D3.1 [6]. INSPIRe also provides the prototype RAIM Prediction Tool which may be implemented by receiver manufacturers as a supporting tool to enable them to provide an availability and coverage forecast for the expected performance of the user-level algorithms.	
User-level algorithms	The user-level algorithms form a part of the internal implementation of receivers and are a necessary part of the receiver firmware. They provide user-level data processing of the GNSS inputs and enable the GNSS performance requirements to be met by the receiver.	No specific standards development activities are required to define the user-level algorithms themselves however there is opportunity to define a recognised algorithmic approach for proving an integrity. This can support receiver manufacturers in meeting the performance requirements, and hence lower the entry barrier to enable receiver manufacturers to meet the GNSS performance requirements. These example algorithms may be published by the IEC as part of the receiver test specifications. To publish a recognised algorithmic approach will require completion of a peer review and validation process similar to that currently underway for A-RAIM to ensure the algorithms are robust. This process will require ongoing review of algorithms through published scientific papers, industry validation and extended performance testing, as well as an authority responsible for assuring and maintaining the algorithms.	INSPIRe has demonstrated several user-level algorithms which may be used as algorithmic approaches for achieving the GNSS performance requirements. INSPIRe has considered the functionality and performance of three user-level algorithms; MG-RAIM, M-RAIM and VAIM. Additionally INSPIRe considers a user-level algorithm for peer-to-peer data sharing to further improve integrity performance. Activities required to mature and adopt these integrity concepts, and further opportunities for improving the performance of an integrity architecture are discussed in section 4.	IEC Receiver manufacturers
User interface with SBAS	Interface of the user's GNSS receiver with SBAS systems, such as EGNOS or UK SBAS, requires a standardised user interface. Existing standards are in place for the minimum performance of SBAS services as developed by ICAO and RTCM (for aviation applications). For EGNOS specifically, ESSP provides service definition documents for the EGNOS Open Service and Safety of Life services.	The IEC has developed 61108-7 to define a standardised set of interface requirements for utilising SBAS services including EGNOS V2 in maritime applications. Evolutions of EGNOS are ongoing under the responsibility of EUSPA including the provision of a maritime service and provision of DFMC corrections in EGNOS V3. As discussed in D5.1 [8], users within the UK EEZ are no longer assured for use of the EGNOS Safety of Life service. A UK service (e.g. EGNOS monitor) which provides this Safety of Life guarantee will require interface requirements in order to define how the EGNOS monitor outputs are disseminated to users or how a responsible entity will manage the outputs so that users can react in the event of an EGNOS system failure.	No specific proposals for the development of EGNOS nor SBAS standards are identified within INSPIRe. An appraisal of the benefits of a Maritime SBAS integrity message for maritime users is considered in D2.1 [5]. The EGNOS Monitor proposed within INSPIRe provides a means of providing a Safety of Life guarantee for users of EGNOS services within the UK EEZ. Activities required to implement the EGNOS Monitor are discussed in section 6.2.	IEC EUSPA UK Government
User interface with DIM	The system-level DFMC Integrity Monitor developed in INSPIRe	As a national system, the responsibility for definition and standardisation of the DIM and its user interface falls under the	INSPIRe has set out the proposed implementation for the DIM including proposals	UK Authority

Aspect	Description	Standard development activities proposed	Inputs from INSPIRe	Proposed responsible Entity
	requires a standardised interface with the user-level to enable the DIM message to be disseminated to receivers and processed in user-level algorithms.	system owner, which in this study is assumed to be a UK Authority. The system may be expansible globally, at which point international standardisation will be required, however within the scope of INSPIRe the DIM has been explored for the UK EEZ only. For the benefits of the DIM to be realised and adopted in vessels, an interface standard must be developed to provide specification for the outputs of the DIM service to receiver manufacturers to enable them to develop receivers which can receive DIM messages and correctly interpret the outputs. Any such standard must be recognised and adopted by all vessel traffic entering the UK EEZ for the maximum benefits of the DIM to be realised. Alternatively, if not adopted for all vessels, the DIM may provide capability for specialised use cases where increased integrity is beneficial within the coverage area of the DIM, or for use cases for sectors outside of maritime within the UK where international co-ordination is not required.	for dissemination concepts and the contents of a DIM message. Dissemination is proposed through both e-Navigation concepts (which will require user-level interface requirements) and/or MSI (which will require operational requirements). The implementation plans for the DIM, including the prerequisite activities, are set out in section 6.3.	
Implementation of National Infrastructure	This aspect identifies the design and definition of national system-level integrity services, which within INSPIRe are: • EGNOS Monitor • DIM • RAIM Prediction Tool (if implemented as a public tool)	National systems require publicly available service definitions and/or standards to be established to communicate the functionality and performance of the systems and enable them to be utilised effectively by users, receivers and other relevant stakeholders. National technical design documentation will be required to fully define an operational system and provide a technical justification for the services to underpin the assurance of each service. Any of these systems might be expansible globally, at which point international standardisation will be required.	INSPIRe provides concepts for these national services, with conceptual technical descriptions and proof of concept validation for each service. Proposed implementation plans, including the institutional activities required to develop these services, are outlined in section 6. For the RAIM Prediction Tool to be considered as national infrastructure, a prerequisite of this is wide adoption of the MG-RAIM and/or M-RAIM algorithms, for example through publication and subsequent adoption of these algorithms.	UK Authority
RAIM Prediction Tool	The RAIM Prediction Tool provides a prediction for the performance of the MG-RAIM and M-RAIM algorithms proposed within INSPIRe. Given that the tool depends on the adoption of the MG-RAIM and/or M-RAIM algorithms, INSPIRe proposes two possible approaches for adopting the tool:	The required activities depend on the implementation and responsible entity for the tool, and the adoption of the MG-RAIM and/or M-RAIM algorithms. In the case of a public tool implemented as national or international infrastructure, a specific entity will need to be responsible for the design and interface of the tool and the provision of the service, and thus service definition documents and any applicable interface standards which need to be developed.	INSPIRe provides a prototype RAIM Prediction Tool concept for forecasting the performance of the MG-RAIM and M-RAIM algorithms. The implementation activities required to provide an operational tool are outlined in section 6.1.	Receiver manufacturers <u>OR</u> UK Authority <u>OR</u> IMO

Aspect	Description	Standard development activities proposed	Inputs from INSPIRe	Proposed responsible Entity
	• Publicly available tool which is provided by a responsible authority, considering a standardised approach for providing integrity through the MG-RAIM and M-RAIM algorithms • A tool implemented by receiver manufacturers to provide forecast performance of implemented user-level algorithms	In the case of a tool implemented by receiver manufacturers, the tool becomes part of the product offered by the manufacturer and thus becomes the responsibility of the manufacturer provider to assure the level of safety and functionality of the tool.		

5.4 Process for developing the relevant standards

This section considers the processes required and associated complexities for developing standards at the relevant levels, both internationally through the IMO and IEC, and nationally.

5.4.1 Developing ConOps and Navigation Performance Requirements

5.4.1.1 Activities required

To develop co-ordinated user requirements requires gathering detailed user needs across industry.

Two potential approaches may be considered:

- An update to IMO A.915 may be led by a national member of the IMO. This activity requires a draft update to be proposed, likely requiring formation of a working group to collate the requirements.
- Alternatively a user-centred approach may be used to gather maritime requirements in parallel to IMO activities, seeking input from maritime bodies and users, either nationally or internationally. This will require collating a list of use cases, proposing a set of requirements for each performance attribute and then seeking comment and feedback on these requirements.

5.4.1.2 Estimated timelines

Estimated timelines for developing an update to IMO A.915 could fall within four to six years however this is uncertain depending on needs for industry consultation and the inputs required.

In the meantime, a study could be let to collate the data and use cases required to support the ongoing development of requirements and gather industry support for such an approach.

5.4.1.3 Roles and responsibilities

Stakeholders may include:

- National administrations to consider and support IMO agenda items. International support will also be required throughout the process.
- EUSPA and other relevant parties that may already have supporting information.
- Universities or industry to lead any data collaboration/requirements capture.
- Funding bodies to support the effort required in gathering and combining data.
- Maritime sector (representation bodies, maritime universities, ports and harbours, pilot bodies etc.) to review and support such discussions.

5.4.2 Developing functional and performance standards for GNSS receivers

5.4.2.1 Activities

There is a task required to consolidate and update the existing IMO receiver performance standards. Given the great variation and differences that exist today with the different standards as set out in section 5.1, consideration should be given to consolidate the existing standards into a new generic performance standard.

5.4.2.2 Estimated timelines

Timelines for the completion of a consolidated standard are unclear, however there is a clear need to communicate the benefits of such a standard and thus develop the necessary support.

5.4.2.3 Roles and responsibilities

Stakeholders may include:

- National authorities (to support the work and the agenda item)
- Industry (to support and lead the technical development)
- Maritime sector (to support the need)

5.4.3 Developing test specifications for GNSS receivers

5.4.3.1 Activities required

Updating existing IEC test specifications will require a new agenda item to the IEC secretariat, that will need to be requested by national members or industry.

Typically, small working groups complete the technical work required to develop draft specifications, which will be shared for review and consideration at IEC meetings before being formally agreed and taken forwards for international review.

5.4.3.2 Estimated timelines

The INSPIRe consortium's experience suggest that establishing IEC standards can take anywhere from four to six years. This timeline includes raising a new agenda item to the IEC secretariat and a two-year completion window.

5.4.3.3 Roles and responsibilities

Stakeholders may include:

- National authorities (to support the work and the agenda item)
- Industry (to support and lead the technical development)
- Maritime sector (to support the need)

5.4.4 Developing standards for UK national infrastructure

5.4.4.1 Activities required

Development of national standards is likely to fall to the UK's Department for Transport (DfT) or an executive agency, such as the Maritime and Coastguard Agency (MCA).

When developing national standards, consideration needs to be given to the need for interoperability and the challenges associated with international adoption, recognising the international operation of vessels.

5.4.4.2 Estimated timelines

The timelines will depend on the agreed approach and whether any outcome requires changes to national legislation or can be implemented within current statute. Advice would be required from DfT and MCA.

5.4.4.3 Roles and responsibilities

Stakeholders would be DfT and MCA, along with maritime user groups and industry representatives.

5.5 Recommendations for developing the maritime navigation standards

The proposed approach outlined in Table 7 identifies several step changes in the extant maritime navigation standards. These each provide opportunity to improve the specificity of and co-ordinate the maritime navigation standards to enable a coherent and consistent approach to maritime navigation performance.

In summary, four key recommendations for developing the maritime navigation standards are identified:

- 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
- 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 siting 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.
- 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.
- 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.

Upon agreement of operational concepts for maritime navigation both internationally and nationally, this will form a vision which will inform a detailed approach and set of activities to develop the maritime navigation standards. INSPIRe has investigated the elements of this relevant to GNSS integrity however wider consideration needs to be given for a resilient PNT architecture.

The process to develop the standards needs to be considered over a long-term timeline considering the necessary ongoing development and validation activities, stakeholder engagements and standard development timelines within the IMO and IEC.

6 IMPLEMENTING THE SYSTEM-LEVEL AND SUPPORTING INTEGRITY CONCEPTS

This section identifies the activities required to implement the system-level integrity and supporting integrity concepts.

6.1 Implementing the RAIM Performance Prediction Tool

6.1.1 Overview of the RAIM Performance Prediction Tool

The RAIM Performance Prediction Tool is a prototype software tool which forecasts the expected integrity performance of the MG-RAIM and M-RAIM algorithms based on the available satellite geometry and satellite visibility.

The tool is configured based on the user-level algorithm in use (MG-RAIM or M-RAIM), input error models (in the case of M-RAIM) and the required navigation performance band.

The tool has two modes of operation:

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

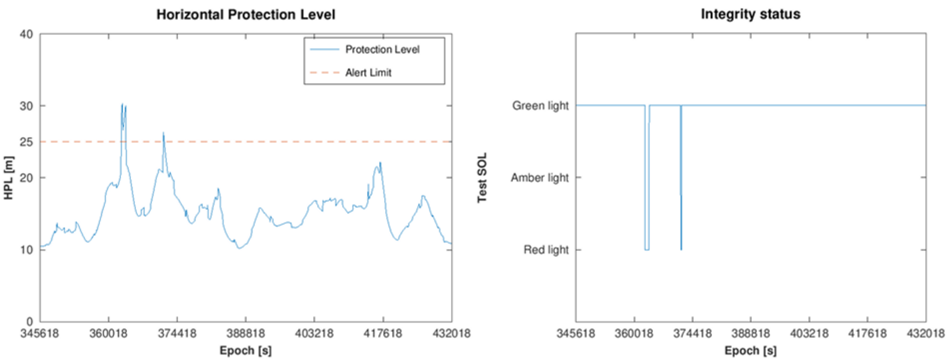

Figure 6 - Example output of RAIM Performance Prediction Tool in Single User mode using the MRAIM algorithm

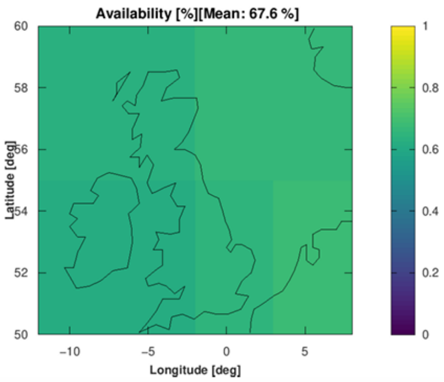

Figure 7 - Example output of the RAIM Performance Prediction Tool in User Grid mode using the MRAIM algorithm over the UK geography

The tool outputs the following predicted parameters:

- 95% accuracy performance;
- Satellite visibility;
- Dilution of Precision (M-RAIM only);
- 99.8% Horizontal Protection Level (M-RAIM only);
- Integrity status (red, amber or green); and
- Availability of green integrity status.

6.1.2 Implementation Roadmap

INSPIRe has developed the RAIM Performance Prediction Tool as a prototype tool. There are two key stages required to develop an operational RAIM Performance Prediction Tool:

- 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.
- 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 requires one or both of the MG-RAIM and M-RAIM algorithms to be incorporated into users' receivers.

The implementation roadmap does not propose a specific owner of the RAIM Performance Prediction Tool. This is because the adoption of the tool is dependent on the adoption of the MG-RAIM and/or M-RAIM algorithms, for example if the algorithms are prescribed by standards or if they are adopted as proprietary solutions by receiver manufacturers. The exploitation opportunities for the RAIM Performance Prediction Tool, and hence the entity which could be responsible for operating the tool, are explored in Section 5.3.

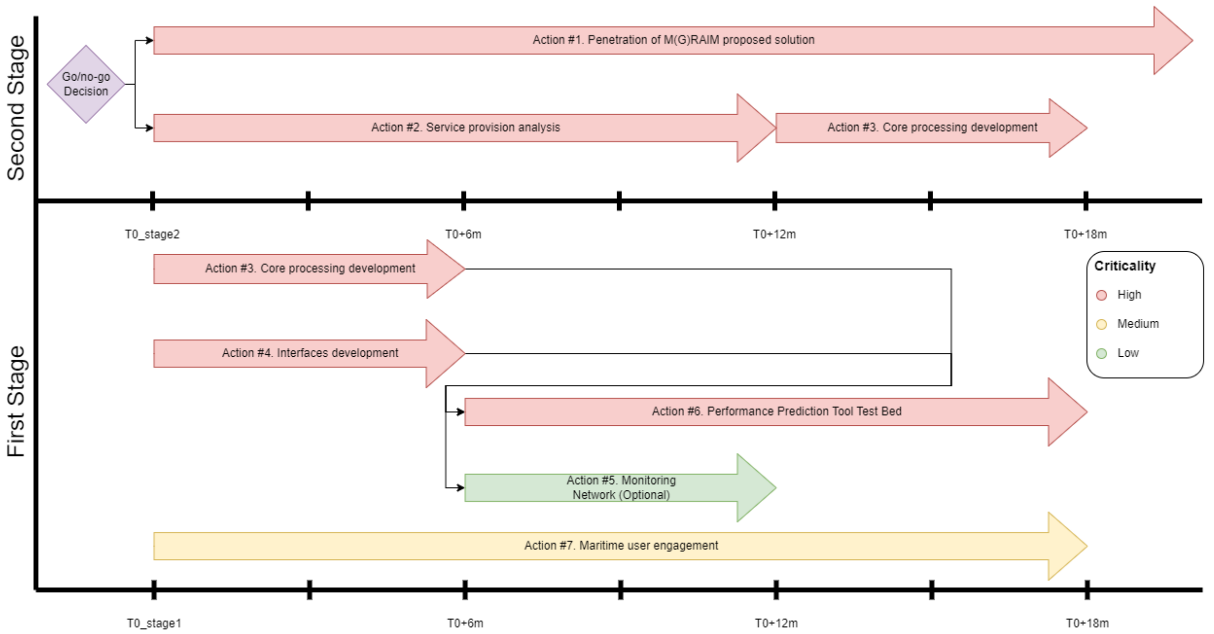

Figure 8 - Operational RAIM Performance Prediction Tool Roadmap

6.1.3 Activities required to develop an operational RAIM Prediction Tool

As detailed in D6.1[7], seven actions are needed to develop the prototype RAIM Prediction Tool to operational status. A summary of these actions is provided below.

6.1.3.1 Action #1. Adoption of the user-level algorithms

Given the RAIM Prediction Tool provides a performance prediction of the MG-RAIM and M-RAIM algorithms, adoption of these algorithms amongst the maritime community is required to foster the need for a RAIM Prediction Tool. As discussed in section 5.3 there are opportunities to publish the user-level algorithms as example integrity approaches within maritime standards, or receiver manufacturers may choose to adopt the algorithms based on the results of INSPIRe.

6.1.3.2 Action #2. Service provision analysis

The service provision scheme for the RAIM Prediction Tool needs to be analysed to identify the requirements and liabilities associated with the tool. This process needs to include stakeholders involved in the service provision, including service providers and users to establish the liabilities and interfaces among them associated with the use of the tool.

This activity is especially critical to determine the liabilities associated with providing a performance forecast and establish appropriate requirements for the system.

6.1.3.3 Action #3. RAIM Prediction Tool core processing development

The tool is currently developed as a prototype. In order to provide an operational tool, the core forecast module must be coded according to the requirements, including verification, safety and operational requirements, defined by Action #2. Service provision analysis.

It should be noted that the tool must be kept aligned with the implementation of the MG-RAIM and M-RAIM algorithms and any error models to provide an accurate performance prediction.

6.1.3.4 Action #4. Development of RAIM Prediction Tool interfaces

This action is to develop the interfaces required to ensure the operation of the tool in accordance with the requirements defined by Action #2. Service provision analysis. There are two groups of interfaces:

- GNSS Healthy Interfaces – inputs required for the tool:
    - GNSS Navigation Interface
    - GNSS Health Status
    - Error models
- User interfaces – outputs to the maritime user
    - Web-based graphical user interface
    - Other output reports and files

6.1.3.5 Action #5. Deployment of monitoring network stations

This action develops a monitoring network to monitor the real performances and compare it against the forecast, in order to fine tune and refine the used error models based on the local environment to receivers. This will enable the performance of the tool to be validated and improved over time, however, is not essential to initial operations.

6.1.3.6 Action #6. RAIM Prediction Tool Test Bed

This action develops a Test Bed to assess the functioning of the tool prior to its operational phase. This will enable the tool's functionality to be evaluated under an operational environment, and assess its capability to support safe navigation. This activity is key to solve any undetected problems in the development phase.

6.1.3.7 Action #7. Maritime user engagement

Throughout the development and implementation of the tool this action is to promote the prediction service and its benefits to ensure adoption of the tool and to ensure consultation to ensure complete requirements are collected through the development phases.

This will ensure the benefits of the tool are effectively communicated to mariners to promote adoption of, and trust in, the tool in the maritime community.

6.2 Implementing the UK EGNOS Monitor

6.2.1 Overview of the UK EGNOS Monitor

The UK EGNOS Monitor developed within INSPIRe proposes a technical means for a UK Authority (as a liable entity) to provide a Safety-of-Life guarantee to users of EGNOS within the UK EEZ, in absence of the UK's participation in the EGNOS programme.

The initial deployment of the EGNOS Monitor aims to enable the aviation services LPV-200 and APV-I for aircraft approach and landing procedures to be re-established in the UK, re-instating the capability which was lost when the UK departed the EGNOS programme.

The roadmap then proposes that the EGNOS Monitor is expanded to services outside of aviation, including maritime.

There are two primary components in the UK EGNOS Monitor:

- A UK based monitoring network implementing a User Position Monitor (UPM) to independently verify 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 Safety of Life guarantee can be made to users by the UK EGNOS Monitor

6.2.2 Implementation Roadmap for the UK EGNOS Monitor

This section presents the roadmap for implementing the UK EGNOS Monitor.

The following constituent components of the EGNOS Monitor must be implemented to enable full functionality of the system to be realised:

- Six monitor sites, each consisting of a control server, three EGNOS receivers (primary, backup and standby), and associated hardware such as cabling, cabinets, power and data communications.
- Two control centres, consisting of server machines hosted at secure locations, a workstation to access the system, a 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 EGNOS Availability 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.

Seven key steps required to implement the EGNOS Monitor are identified. These steps represent initial estimates for the activities and timelines required to roll-out the system:

- A cooling off period after the INSPIRe project is required to peer-review the EGNOS Monitor proposal and garner support for commissioning the system. (+6 months)
- Establish a legal and regulatory framework for a UK government *liable entity*, which must include framing the terms of an EGNOS SoL guarantee for UK users. (+6 months)
- A tendering process for the delivery of the system will be required, including specification, contract negotiations and project initiation. (+6 months)
- Delivery of the system including hardware and software components. (+6 months)
- Initial Operating Capability (IOC) during which the achieved UK-validated service region for EGNOS can be empirically established, to inform the final terms of the SoL agreement with users. This process can also include a "soak test" of the monitor

receiver's local noise and multipath models and to verify that the sites selected are free of spurious interference. (+1 year)

- Final Operating Capability (FOC) during which SBAS approaches for UK airports can be re-instated.
- Establishment of cross-sector applications, including a maritime service (can begin once IOC is achieved).

This lays out a timetable to be able to re-establish EGNOS SoL approaches for UK airports within three years of the end of INSPIRe. Development of cross-sector applications, including a maritime service can then begin once IOC of the system is declared.

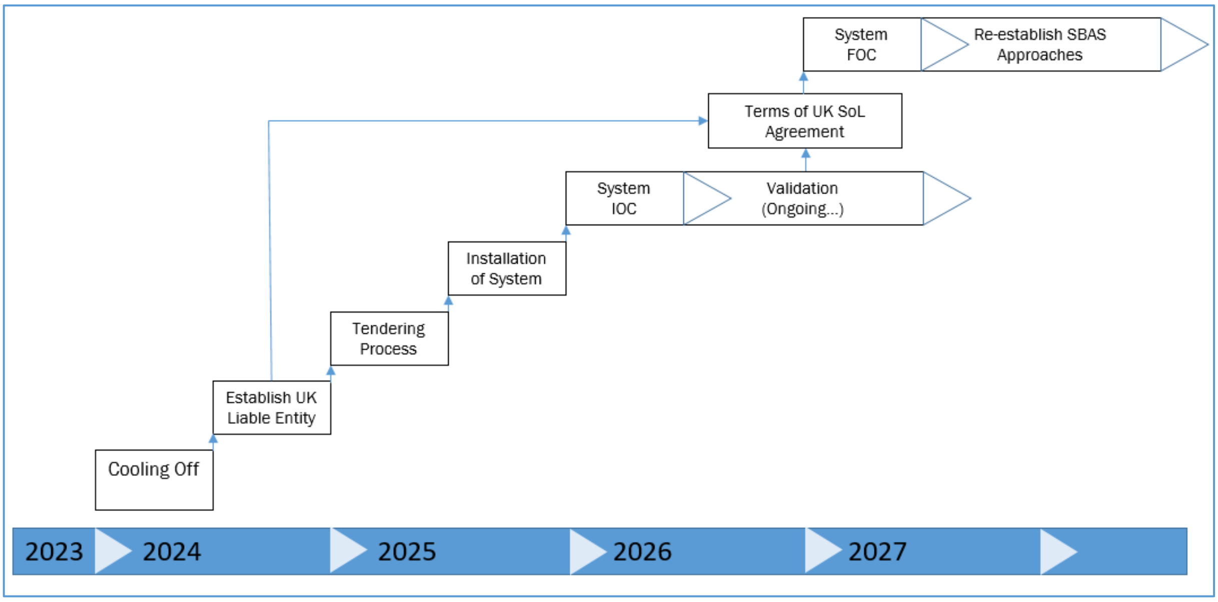

Figure 9 – Indicative timeline for installation of EGNOS monitor system and re-establishing SBAS approaches for UK Aviation

6.2.3 Outline of costs for the UK EGNOS Monitor

The estimated costs for the UK EGNOS Monitor is £5.8m over a 20-year service period.

The costings include approximately £750k of CAPEX for the development of the system with ongoing £200k of OPEX per annum.

These costs are based on a development approach which aims to produce a functional system with a degree of validation, and a different development approach will require the costings to be re-estimated.

6.3 Implementing the DFMC Integrity Monitor

6.3.1 Overview of the DIM Service

The DFMC Integrity Monitor (DIM) service sets out a proposal for a shore-based integrity monitoring system which utilises integrity monitoring stations sited throughout the UK.

The integrity monitoring stations are highly validated GNSS receivers which provide input data to a centralised control centre. The control centre completes an Integrity Check Function which compares the data received from the integrity monitoring stations to International GNSS Service (IGS) data, historical archive data, and internal configuration data to determine the integrity of the data provided by each GNSS satellite, and generate an integrity notification message.

The integrity notification message can be disseminated to users via:

- MSI as Radio Navigation Warnings (RNWs); and/or
- e-Navigation services as an Integrity Support Message (ISM).

The integrity notification messages provide users with integrity information for the satellites which are in view of the DIM's integrity monitoring stations, with the RNW providing a human readable indication of long-term GNSS faults or constellation failures, and the ISM providing a live integrity status for each satellite in view of the DIM.

The DIM requires several key functions to be implemented:

- DFMC Integrity Monitoring Stations;
- Central Configuration and Processing Facility;
- Dissemination Service (MSI and/or e-Navigation); and
- a Competent Authority, responsible for the Institutional Framework required to support the DIM.

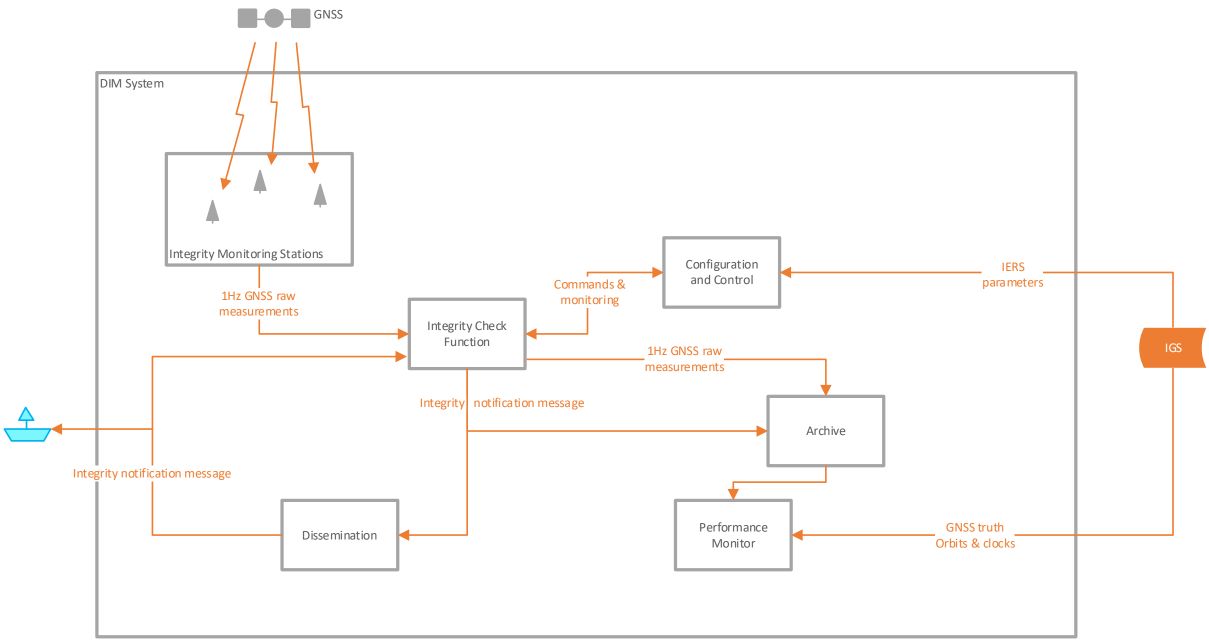

Figure 10 - DIM conceptual architecture

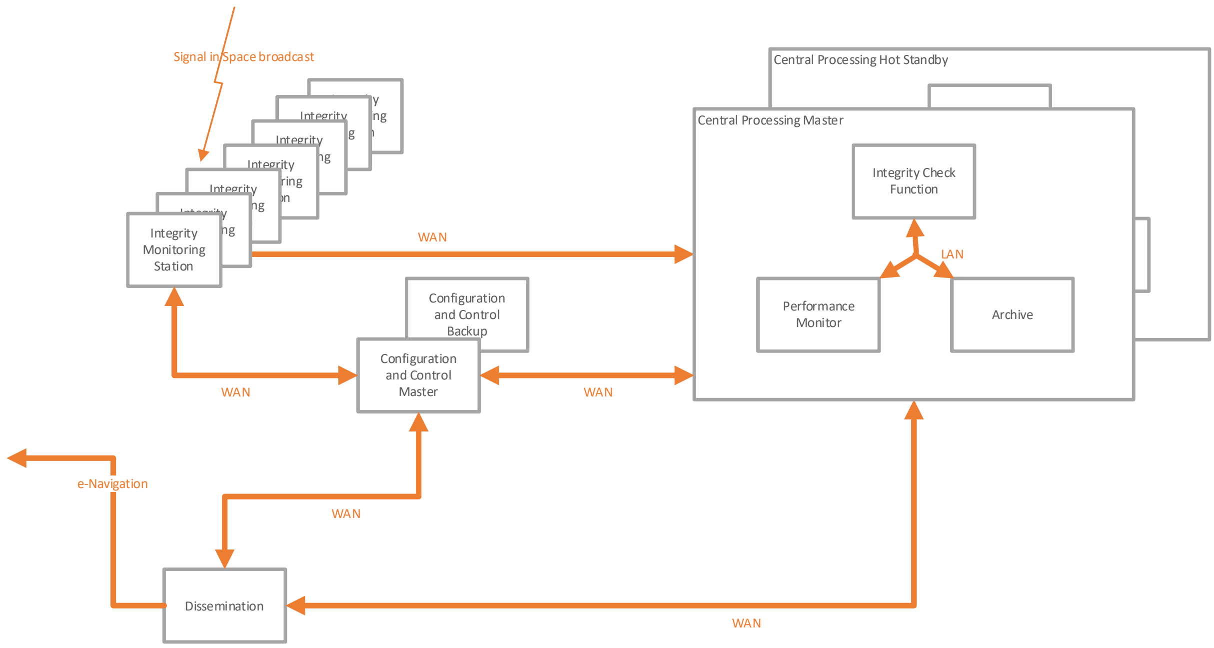

Figure 11- DIM high level physical architecture

6.3.2 Implementation Plan Schedule and Work Logic

6.3.2.1 Dependencies for the DIM Service Implementation

The key dependencies of the workflow are highlighted below:

- 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.

6.3.3 Technological and Environmental Research

The development of a DIM service will require the following activities to be completed:

6.3.3.1 Receiver, Antenna and Clock Hardware

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

- Clock Steering;
- Autonomous detection of measurement quality degradation, for example due to multipath, cycle slip, or jamming;

- Evil-wave form detection capability; and
- Capacity to track at least 12 channels per constellation, and all signals / frequencies which the DIM Service is designed to support.

Whilst suitable receivers likely exist, they need to be sourced and may require customisation to meet the needs of the DIM.

6.3.3.2 Site surveys

At least seven monitoring sites need to be identified and surveyed to determine their suitability for the DIM. Considerations needs to include geographic location, robust communications facilities, maintainability and other supporting infrastructure. The sites also need to be assessed with regards to their exposure to multipath and other forms of interference, including intentional or unintentional jamming. Site surveys require extended periods of monitoring due to for example the seasonal variability of vegetation.

6.3.3.3 Algorithmic Enhancements

A number of algorithmic areas which may benefit from additional dedicated research were also identified through the proof of concept study. These topics are:

- A dedicated trade-off between reducing the false alarm probability and improving satellite availability: The optimum criteria and tuning for this trade-off remain to be finalised.
- Pseudorange smoothing may in certain exceptional circumstances degrade the accuracy of the satellite modelling. Research could either construct a suitable algorithmic barrier or quantify the inherent integrity risk.
- Some extreme satellite error conditions generate significant differences in satellite residual across UK EEZ. The algorithm tested in INSPIRe is not able to recognise such a trend, and is partly limited by the footprint of observations. Further research into an algorithmic barrier should be conducted to identify exceptionally strong trends in the residuals' data.
- Further research should be conducted into the stability of the station clock models smoothing the acquisition and loss of satellite lines of sight from a given station.

6.3.3.4 Proof of Performance

The Proof of Concept Testbed developed within INSPIRe estimated and extrapolated the DIM Service performance on the basis of significantly unrepresentative data. Further development of a complete representative performance simulation environment is therefore critically important to underpin the performance models. The key criteria for the collation and generation of test data are:

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

This data will enable performance of the DIM service to be proven through the three key service performance elements; proof of integrity, proof of false alarm rate, and distribution of feared events.

6.3.4 DIM Institutional Framework

A maritime safety of life service provided by the DIM Service requires governance through a comprehensive institutional framework.

6.3.4.1 User Interface Standards

An interface standard for maritime users will need to be established. This will enable equipment manufacturers to develop user receivers capable of processing the DIM Service messages, and ensure that user receivers interpret the provided integrity assurance information correctly when computing protection levels. The new standard must address the following topics:

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

A competent authority which is in a position to adopt the standard will need to be identified and engaged at the earliest opportunity.

6.3.4.2 Qualification and Certification

The DIM Service will need to be certified, this process comprises two main elements:

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

The DIM Service certification will therefore need to be performed by a suitable certification authority. The certification authority must be identified and engaged before any material development activity commences so that all development, design, procurement, implementation, integration and validation activities will occur under the scope of the certification authority. We expect that qualification and certification will require several years of DIM Service operation before safety-of-life operations can be established.

6.3.4.3 Safety Analysis

A safety analysis of the DIM is required to identify hazards inherent in the system and ensure they are mitigated. A number of design trade-offs are proposed in the design which represent potential CAPEX and OPEX savings. The safety analysis is required to consider the trade-offs in the DIM System design to achieve the overall required level of integrity.

It is essential that the safety analysis is performed both ahead of and during the development of the DIM to guarantee that the required level of integrity is achieved by the system.

6.3.5 DIM Dissemination Service

The dissemination of the DIM service message has two distinct pathways:

- Dissemination of integrity warnings as MSI to provide longer-term status alerts of GNSS integrity or constellation outages, communicated to the mariner with the delays inherent with MSI.
- Dissemination of a live feed of a DIM message as an e-Navigation service to enable live processing in user receivers.

6.3.5.1 Dissemination of Integrity Warning Messages via MSI

MSI dissemination is already well established in the maritime domain with the sea divided into a number of navigational areas (NAVAREAs). The UK sits within NAVAREA-I which is coordinated by the British Admiralty, with the practical aspects of MSI dissemination conducted by the UK Hydrographic Office (UKHO).

To establish a DIM message via MSI an interface must be set up with the Admiralty for the dissemination of the message via a set of rules. These rules require the following to be identified and agreed as acceptable to the Admiralty as the NAVAREA co-ordinator:

- content and wording of the MSI;
- how an alert is raised, and also cancelled;
- anticipated frequency of integrity alerts; and
- expectations of both parties as to how rapidly the alert can be disseminated to the mariner.

It will also be necessary to determine a set of rules for the mariner regarding the use of the MSI, including:

- education of the message structure; and
- how mariners should respond to GNSS integrity warnings delivered by MSI.

These rules will require suitable consultation processes with maritime users to ensure that the alerts are suitable and do not cause confusion on the bridge of the ship. A worst case scenario would necessitate changes to the International Convention on Standards of Training, Certification and Watch-keeping for Seafarers (STCW), and new training for mariners in how to implement GNSS integrity warnings in their navigation equipment which might take up to a decade.

6.3.5.2 Dissemination of Integrity Support Messages via e-Navigation

Initially user dissemination of the DIM message as an e-Navigation service could be demonstrated using a Maritime Connectivity Platform (MCP) testbed, one of which is owned and run by GRAD. By using a compatible GNSS receiver connected to the MCP to receive and interpret the integrity data, this would enable the user processing of DIM message to be demonstrated and evaluated.

Establishing a fully operational end-to-end demonstration of dissemination via e-Navigation will take longer to achieve, and depends on two separate development paths:

- Developing a compatible user's receiver, able to interpret the DIM message stream and employ it when fixing the vessel's position using GNSS.
- Deploying an operational MCP, complete with data communications pathways to the user in a maritime environment (for example satellite or mobile telecoms, or VDES).

The first activity is discussed in Section 6.3.4.1.

The second activity requires significant development work to develop the MCP concept to maturity and to establish suitable data communications links with vessels, particularly offshore.

The MCP is overseen by the Maritime Connectivity Platform Consortium (MCC). The MCC oversees establishment of (but does not operate) test instances (one of which is operated by GRAD in the UK) and oversees the development of relevant standards and operating procedures for the MCP. An overview of the basic architecture of the MCP can be seen in Figure 12.

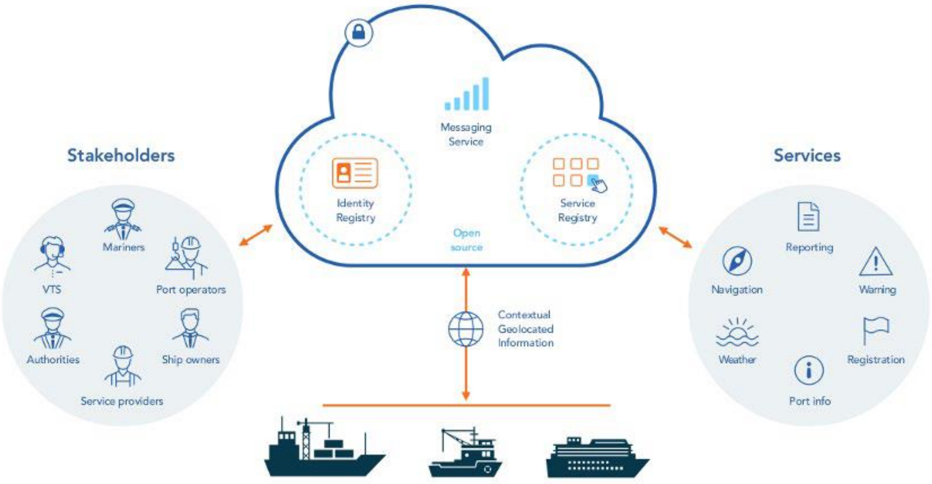

Figure 12 – Basic Architecture of the Maritime Connectivity Platform (MCP)

To establish the DIM message as an e-Navigation service within the MCP two key actions are required:

- 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).
- Listing the service on the Maritime Service Registry (MSR), so that vessels can search for, locate, and subscribe to the e-Navigation service.

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

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

6.3.6 Outline of implementation costs for the DIM

The estimated costs for the DIM service are expected to be £265.5m over the 24-year lifespan, however this cost is uncertain at present as it is significantly dependent on the implementation approach.

The costs presented are loosely estimated based on a percentage of the implementation costs of the SouthPAN SBAS system, assuming a comparable level of development and safety assurance of the system is required.

As noted in the implementation approach, a heavy weighting is placed on qualification and certification of the system and its design to provide a high level of integrity support to the user from the DIM service. The level of assurance required needs to be determined from user requirements and the need for integration with other systems, which will have a significant bearing on the costs for the required development and ongoing maintenance of the system.

6.3.7 Implementation Roadmap for the DIM Service

This section presents an illustrative high-level schedule and workflow for the implementation of the DIM Service.

ID	Task Name	Duration	Start	Finish
1	**Constellation**	**1045 days**	**Mon 01/01/24**	**Sat 01/01/28**
2	GPS Block III launches	1045 days	Mon 01/01/24	Sat 01/01/28
3	**Institutional Oversight**	**2348 days**	**Mon 01/01/24**	**Wed 29/12/...**
4	**Maritime Standards**	**1306 days**	**Mon 01/01/24**	**Mon 01/01/...**
5	Identify and Engange Competent Authori	263 days	Mon 01/01/24	Wed 01/01/...
6	Define Standard	263 days	Mon 01/01/24	Wed 01/01/...
7	Standard Adoption	1043 days	Thu 02/01/25	Mon 01/01/29
8	**Qualification and Certification**	**2348 days**	**Mon 01/01/24**	**Wed 29/12/...**
9	Identify and Engange Competent Authori	263 days	Mon 01/01/24	Wed 01/01/...
10	Accompany Development	1826 days	Thu 02/01/25	Thu 01/01/32
11	DIM System Qualification	131 days	Tue 30/12/31	Tue 29/06/32
12	DIM Service Certification	131 days	Wed 30/06/32	Wed 29/12/...
13	**Dissemination**	**263 days**	**Mon 01/01/24**	**Wed 01/01/...**
14	Identify and Engange Competent Authori	263 days	Mon 01/01/24	Wed 01/01/...
15	**DIM System**	**2349 days**	**Mon 01/01/24**	**Thu 30/12/32**
16	Kick-off	0 days	Mon 01/01/24	Mon 01/01/24
17	**Research**	**329 days**	**Mon 01/01/24**	**Thu 03/04/25**
18	Algorithmic Experimentation	131 days	Mon 01/01/24	Mon 01/07/24
19	Final Performance Model	66 days	Thu 02/01/25	Thu 03/04/25
20	**IMS Stations**	**1306 days**	**Mon 01/01/24**	**Mon 01/01/...**
21	Hardware Prototyping	131 days	Mon 01/01/24	Mon 01/07/24
22	Site Surveys	263 days	Mon 01/01/24	Wed 01/01/...
23	Site Acquisition	522 days	Thu 02/01/25	Fri 01/01/27
24	Hardware Production	522 days	Thu 02/01/25	Fri 01/01/27
25	Deployment	521 days	Mon 04/01/27	Mon 01/01/29
26	**Central Processing**	**1306 days**	**Mon 01/01/24**	**Mon 01/01/...**
27	Safety Modelling	301 days	Tue 14/05/24	Tue 08/07/25
28	Technology Prototyping	350 days	Mon 01/01/24	Fri 02/05/25
29	Specification and Architecture	261 days	Thu 02/01/25	Thu 01/01/26
30	Implementation	782 days	Fri 02/01/26	Mon 01/01/29
31	**Dissemination**	**1043 days**	**Thu 02/01/25**	**Mon 01/01/...**
32	Implement e-navigation	1043 days	Thu 02/01/25	Mon 01/01/29
33	**System Integration**	263 days	Tue 02/01/29	Thu 03/01/30
34	**Non-SoL Operation**	780 days	Fri 04/01/30	Thu 30/12/32
35	**DIM Service**	**11307 days**	**Tue 28/12/27**	**Wed 29/04/...**
36	Incorporate Service Operator	1045 days	Tue 28/12/27	Tue 30/12/31
37	Safety-of-Life Operations	10000 days	Thu 30/12/32	Wed 29/04/...

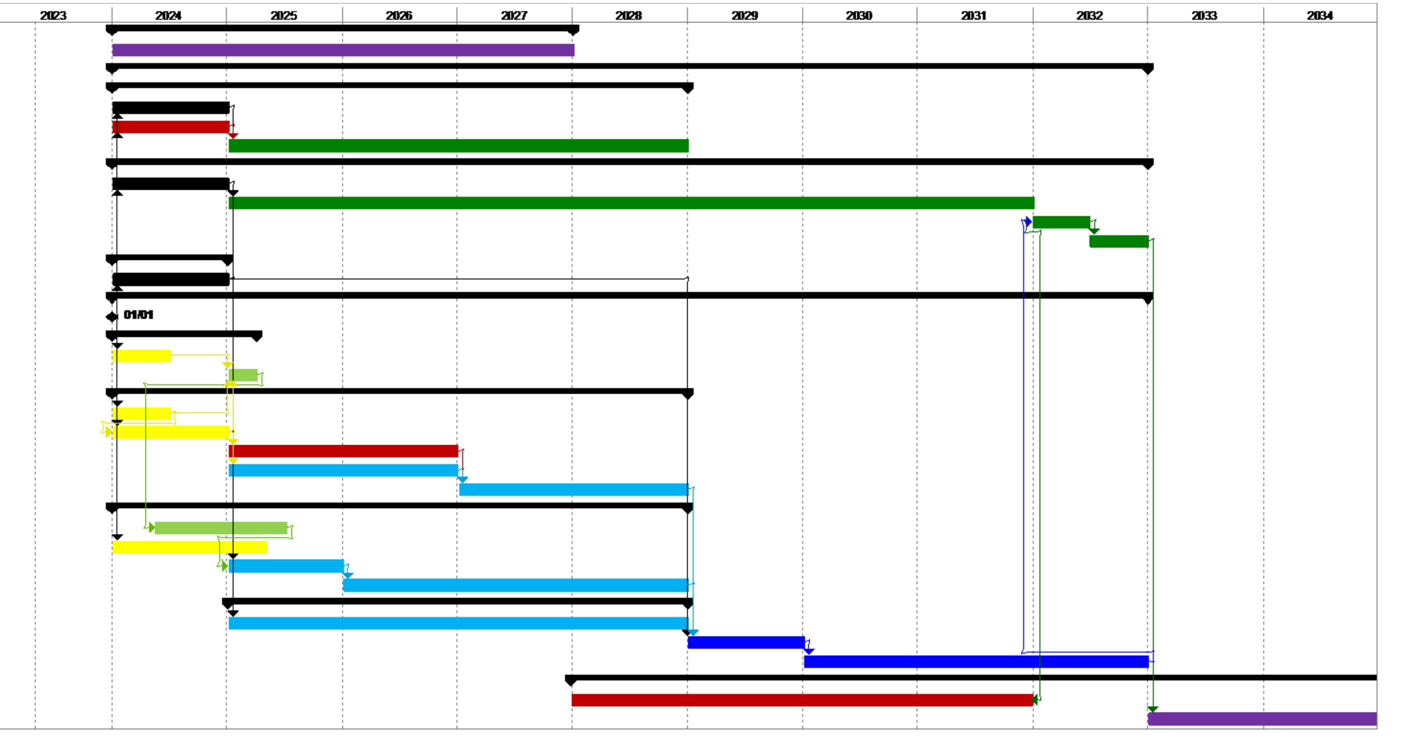

Figure 13 – Illustrative DIM Service Schedule

6.3.8 Further development opportunities at the system-level

Further to the DIM Service developed in D7.1[8] further investigation has been undertaken within D8.1[9] 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.

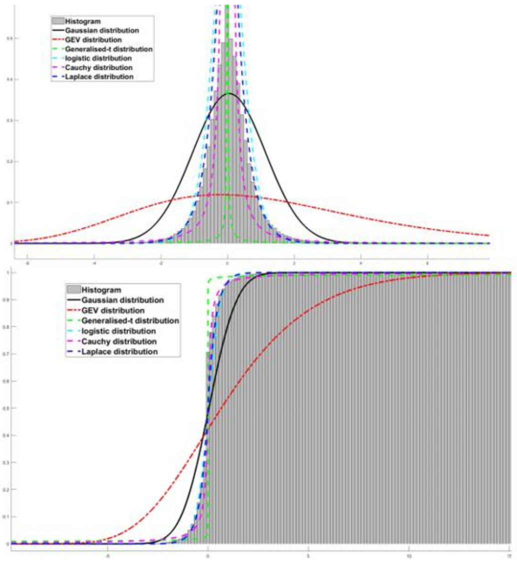

Figure 14 - Pseudorange error characterisation using the six distributions in PDF and CDF domain

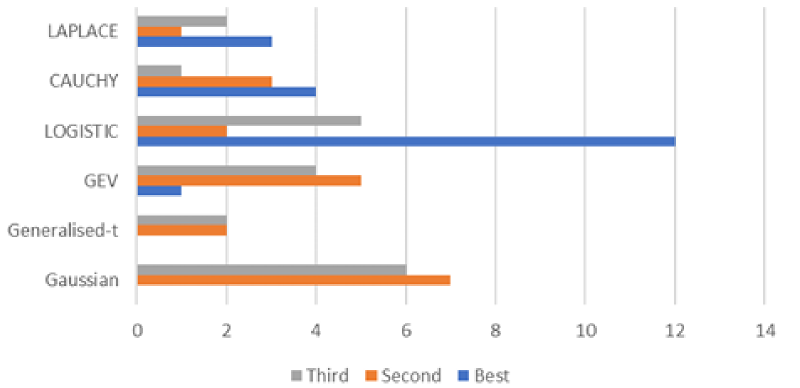

Figure 15 - Number of times with which each distribution ranked as the best, second best, and third best in terms of dataset fitting

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.

Several activities are proposed to further improve the performance of and thus implement these alternative error characterisations:

- 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.

These activities should be implemented considering opportunities for continuous improvement (for example using Machine Learning), and using a phased roll out to enable the error characterisation methods to be adopted and tested in controlled environments.

7 CO-ORDINATED IMPLEMENTATION ROADMAP

This section presents a co-ordinated roadmap for implementing all components of INSPIRe's integrity architecture. It aims for a progressive adoption of user-level integrity amongst both the non-regulated and regulated (SOLAS) maritime sectors. This roadmap is presented in Figure 16.

The roadmap co-ordinates development of the integrity concepts to ensure that the components of the architecture are designed and implemented in harmony according to common user requirements. The roadmap also presents opportunities to align development activities between the components to reduce overall costs and timelines.

Throughout implementation it is critical to maintain close engagement with relevant stakeholders, including:

- **Users from maritime and other sectors** to ensure that suitable requirements are adopted across the integrity architecture such that functionality and performance align with current use cases, and that requirements will align with future use cases as they are developed and emerge.
- **Receiver manufacturers** to ensure that development of the integrity components is feasible for implementation and can be supported through the standards development processes.
- **PNT communities** to provide technical inputs, advancement opportunities and peer review throughout the development processes.
- **Certification Bodies** to ensure that safety and performance requirements are met through design and validation phases, and that a robust development and risk management process is followed.
- **UK Competent Authorities** to support standards proposals to the IMO and IEC, lead development of national system-level components, and to ensure that suitable liability provisions are in place for Safety-of-Life operations.
- **International Regulators** to ensure that the integrity architecture is developed in alignment with international approaches and user-level components can be standardised.

This roadmap shows that it is possible to exploit user-level components of the integrity architecture within a very short timeline in non-regulated use cases, particularly MG-RAIM, to represent near-immediate improvements in integrity performance.

As each of the system-level components come online and as the user-level algorithms and standards are matured, the roadmap represents progressive improvements in integrity performance.

The timelines for developing international standards is driven by the need for national and international industry support, the timelines required for raising proposals to the IMO and IEC, and potential needs for dependencies such as a better understanding of the maritime environment. For the purpose of this roadmap, the timelines for each standards development activity are estimated to be approximately four to six years based on previous experience, but this may vary. Based on these estimates, early adoption of user-level integrity in the regulated market might be possible within a four to six year timeline, with a continued adoption after this as standards and system-level solutions are further matured and implemented.

	Duration	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Developing the integrity concepts to maturity													
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												
Developing the institutional framework													
Attribute responsibilities to UK Competent Authorities and Certification Bodies	1 year												
Certification and safety-of-life assurance activities	Ongoing												
Manage project implementations	Ongoing												
Developing international user-level standards													
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												
Implementing national system-level integrity concepts and supporting tools													
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												
Fostering adoption of the user-level integrity concepts													
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 16 - Indicative roadmap for implementing the INSPIRe integrity architecture

8 MARITIME EXPLOITATION OPPORTUNITIES

This section outlines the exploitation opportunities in the maritime sector for the integrity concepts developed by INSPIRe. It addresses:

- target markets for the integrity concepts;
- the emerging PNT policy framework in the UK; and
- the route to market, considering the additional development needed and enablers such as standardisation.

8.1 Target markets

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.

The potential markets for each of the INSPIRe concepts are summarised below.

8.1.1 MG-RAIM, M-RAIM and VAIM

These are user level integrity concepts. They 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. They will have global application. Note that RAIM is already present in most maritime GNSS receivers but is not standardised and does not have associated performance requirements. There is a market opportunity, therefore, for a standardised maritime RAIM solution of proven performance, especially in the light of the cessation of the IALA DGNSS service and lack of coverage or acceptability of SBAS solutions (both of which only provide system-level integrity in any case).

The principal application for these user-level integrity concepts will likely be general navigation for both crewed and autonomous vessels. GNSS is the primary source of positioning information in sea navigation. In the case of Safety of Life at Sea (SOLAS) vessels: all passenger ships, and cargo ships larger than 500 gross tonnage or larger than 300 tonnes if engaged on international voyages are regulated and heavily rely on GNSS to support navigation activities. At least three devices are typically fitted on vessels for redundancy reasons. 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.

8.1.2 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 directly to users or through Maritime Safety Information (MSI). This system is akin to, but more sophisticated than, the IALA DGNSS system that uses medium-frequency (MF) radiobeacons to transmit local integrity information to GNSS users. This system is likely being wound down because of the high operations and maintenance costs and the perceived redundancy of the service in the light of SBAS and RAIM. The service was discontinued in the UK on 31 March 2022.

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 or future applications of e-Navigation concepts.

8.1.3 A UK EGNOS Monitor

This is a system-level integrity monitoring concept which monitors the outputs of EGNOS to provide means for a UK Authority 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 (see the UK policy statement below).

8.1.4 Peer-to-peer communications

Peer-to-peer communications (also referred to as crowdsourcing) can be categorised into user-level and system-level types, which can be defined as follows:

- User-level peer-to-peer communications rely on leveraging nearby GNSS devices to support the user-level navigation system by using positioning information from nearby users. INSPIRe has considered a method of user-level peer-to-peer communications using AIS communications and ranging data.
- System-level crowdsourcing involves the use of any available PNT sources to support system-level integrity monitoring.

Peer-to-peer integrity concepts offer the potential to support a wide range of mission-critical use cases in maritime and across other sectors (including aviation, autonomous vehicles, robotics, precision agriculture, and autonomous drone operations; see the next section for an introduction to some of these).

For use cases where performance requirements are met, system-level crowdsourcing can reduce the alarm limit requirements in future, which can enhance operations. For use cases where the performance requirements are not currently met, system-level crowdsourcing can be a key element in achieving these performance levels in the future.

User-level crowdsourcing positioning has the potential to support a wide range of PNT applications in the future as connectivity between vessels, people and infrastructure evolves. The advantage of this user-level approach is rooted in the limitation that standalone GNSS systems cannot achieve the requirements for high-accuracy applications, especially within challenging environments.

8.1.5 Supporting tools

The RAIM Performance Prediction Tool investigated by INSPIRe is a software tool that forecasts the integrity performance for a user utilising the MG-RAIM or M-RAIM algorithms based on satellite visibility and geometry, enabling users to predict the performance of their positioning solution over a mission. This is analogous to the AUGUR RAIM prediction tool/service provided by EUROCONTROL in the aviation sector. This tool will likely be useful 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 MSI notifications. The deployment of the RAIM prediction tool is dependent on the adoption of MG-RAIM and M-RAIM.

8.2 Opportunities arising from the emerging UK policy framework

UK government has recently released its policy framework for greater resilience in PNT [23]. 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 policy framework is based on the following ten measures:

- establish a National PNT Office in the Department for Science, Innovation and Technology – to improve resilience and drive growth with responsibility for PNT policy, coordination, and delivery.
- retain and update of a cross-government PNT Crisis Plan to be activated if GNSS provided PNT is lost and identify and implement short term mitigations.
- develop a proposal for a National Timing Centre – to provide resilient, terrestrial, sovereign, and high-quality timing for the UK including sovereign components and optical clocks.
- develop a proposal for 'Ministry of Defence Time' creating deeper resilience through a system of last resort and use National Timing Centre provided timing to support the Ministry of Defence.
- develop a proposal for a resilient, terrestrial, and sovereign e-Loran system to provide backup Position and Navigation.
- rollout resilient GNSS receiver chips, develop holdover clocks, and consider options for legislation on critical national infrastructure (CNI) sectors to require minimum resilient PNT.
- develop a proposal for a UK precise point positioning (PPP) SBAS to replace the UK's use of EGNOS, monitor GNSS and enable GNSS dependent high accuracy Position for autonomous and precision uses.
- explore options for Centres for Doctoral Training in PNT and review PNT skills, education, and training for long term sovereign PNT capability.
- develop a PNT growth policy, including R&D programmes, standards and testing, to drive innovation for PNT based productivity.
- deploy existing R&D funding into a UK Quantum Navigator and investigate possible options for a UK sovereign regional satellite system.

This new framework provides several exploitation opportunities for INSPIRe:

- by providing a central focal point where PNT cross-sector needs and opportunities can be consolidated and addressed. This can be a platform to enable the INSPIRe concepts to access other sectors where they may find application (see Section 9) and, conversely, enable other sectors to understand the potential for the INSPIRe concepts in their sectors. This can also promote efficiency by avoiding duplication and re-invention of the wheel by cross sector research and innovation (R&I) coordination.

- 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 (see below).
- 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.

8.3 Getting to market – overcoming the valley of death

As illustrated in Figure 17, 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 "valley of death" is the gap between academic or upstream research and commercialisation. During this phase, the costs associated with testing and demonstrating new technology in representative or real environments can be problematic. This is because the development cycle falls between the regime where public-funded research is legitimate and the regime where industry can be expected to make a reasonable rate of return relatively quickly.

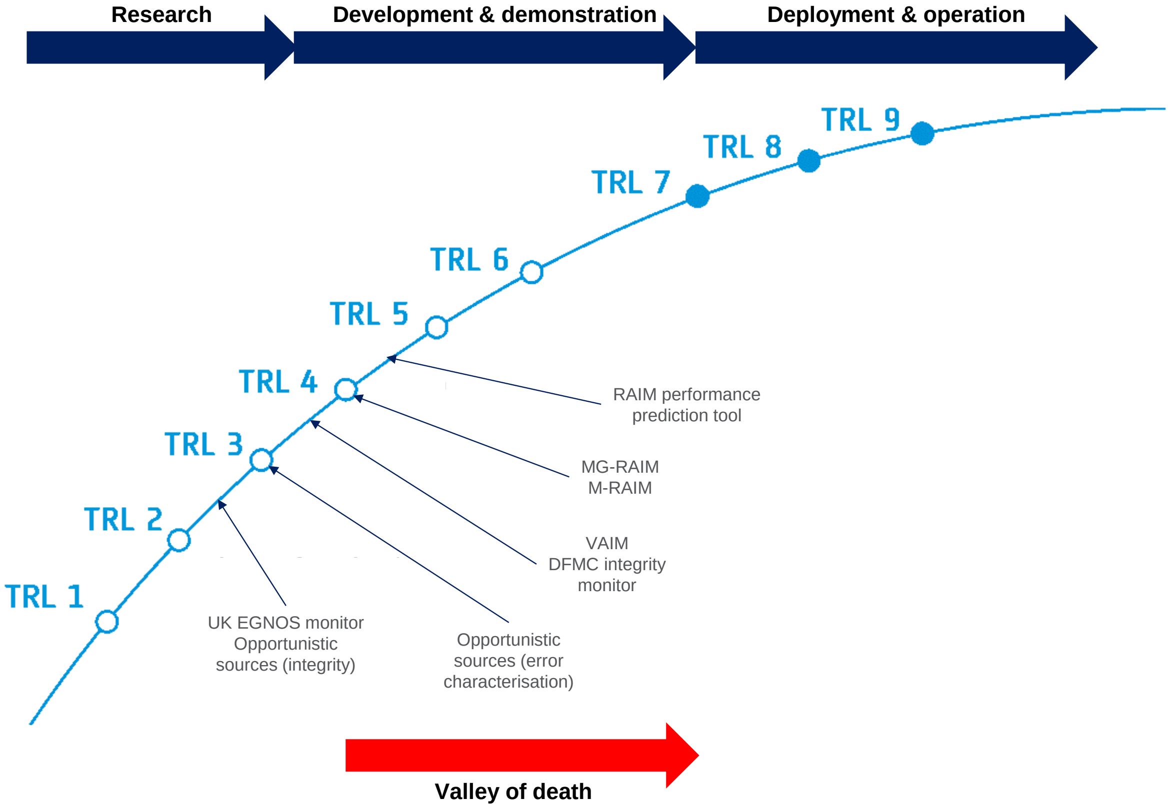

Figure 17 - TRL of the INSPIRe integrity concepts, illustrating the "valley of death"

One of the causes of the valley of death is often cited as the difference in objectives and ways of working between the research organisations undertaking the low TRL tasks and industry and commercial organisations taking the concept to market. INSPIRe addressed this potential shortcoming from the outset by combining academia, research, public service and market-driven industrial partners in the team.

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 concepts towards the market.

8.4 Getting to market – 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. In simple terms, a contracting state needs to make a proposal to the IMO concerning the onboard equipment. If accepted, IMO will act on the proposal and develop and publish performance requirements. These performance requirements are then used to develop test specifications by the IEC as the basis for industry to develop equipment and that equipment to be certified by national maritime administrations. 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.

8.5 Market size – opportunities for industry

The following chart, taken from EUSPA's 2024 market report [22] shows the historic size of global markets in onboard units sold per year in the maritime sector.

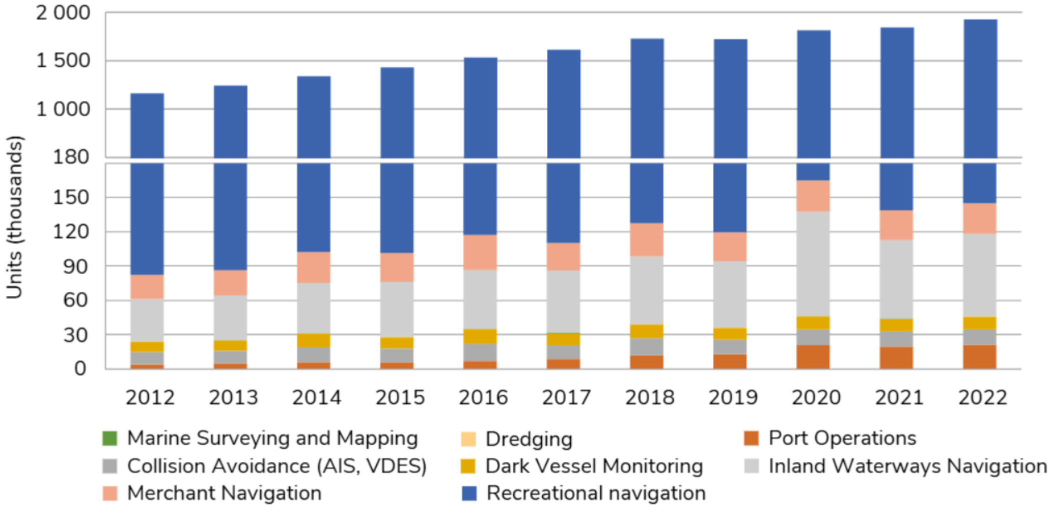

Figure 18 - Historic size of global markets for maritime receivers, Source: EUSPA Market Report 2024

The chart shows that merchant navigation, which is the category that most closely fits the SOLAS general navigation market segment, has remained flat over the 10-years illustrated with sales at around 25,000 units per year. This is the segment where MG-RAIM, M-RAIM and VAIM are most likely to be mandated.

Unsurprisingly the recreational sector is by far the largest with over one million units sold per year. 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.

9 OPPORTUNITIES OUTSIDE THE MARITIME SECTOR

The INSPIRe project 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; that is where PNT failure – specifically operational errors caused by undetected hazardously misleading information – has the risk of severe negative consequences in one of more performance dimensions. The most obvious of these are safety and security but other critical dimensions might include, for example:

- environmental protection;
- legally binding verification of data across sectors, for example in criminal legal cases, insurance claims and the timing or location of financial transactions; and
- operational efficiency, for example in tracking of goods in just-in-time logistics operations.

With its focus on the maritime sector, INSPIRe has addressed the specific factors that make maritime PNT integrity different to PNT integrity in, say, the aviation sector. These factors mean that aviation PNT integrity concepts cannot simply be ported to maritime systems. The principal of these factors are: (i) vehicle dynamics, which are less smooth for ships than aircraft and can include large roll, pitch and yaw, and (ii) the multipath environment externally, for example, in ports and internally on board the vessel from superstructures, masts, etc. Other sectors that could present opportunities for INSPIRe concepts should exhibit one or both these properties.

Considering the above, the primary markets where the 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; and
- 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.

9.1 Application of integrity concepts to other sectors

9.1.1 Uncrewed aerial systems and urban air mobility

9.1.1.1 Drones

Uncrewed aerial systems (UAS) (commonly referred to as drones) are becoming ubiquitous with many applications from hobbyists through transport of time-critical cargo, such as blood for transfusions and organs for donation, through to search and rescue. Regulation and associated requirements for UAS are under development at ICAO, EASA and national levels. Currently within Europe three categories of UAS operation are envisaged:

- The **open category** (low risk) comprising small drones (<25kg maximum take-off mass (MTOM)) flying below 400 feet safety is ensured through operational limitations, compliance with industry standards, requirements on certain functionalities, and a minimum set of operational rules. These operations are controlled within visual line-of-sight (VLOS) of the drone pilot so the drone does not need any internal positioning or navigation capability.
- The **specific category** (medium risk) for larger drones, flying above 400 feet or undertaking certain types of operation (e.g. releasing objects during flight) where authorisation for the flight is granted by the national aviation authorities (NAA). Flights in this category requires the operators to be licensed and, more likely than not, extends beyond visual-line-of-sight (BVLOS). The drone pilot, therefore, requires some sort of position reporting from the drone to maintain a situational picture for their drone.
- The **certified category** (higher risk) for vehicles operating in classes A to C of controlled airspace or in other parts of airspace designated by the regulator (so-called U-space in the European Union). U-space is a geographical area where UAS operations are only allowed if they are supported by (certified) U-space services. Here the vehicle and its operation will be treated in a very similar way to creed aviation: the vehicle must be certified; the operator must have an air operator approval and the drone pilot must have a pilot licence.

Drones operating in the specific and certified categories have need to report their position accurately and reliably to their remote pilot and, most likely, to a traffic manager who will be responsible for maintaining the air picture.

Vehicle dynamics: Some drones are very similar to conventional aircraft with similar motion. However, other drones are much nimbler, having the ability to hover, fly sideways and backwards.

Aircraft-like drone

Nimble, parcel delivery drone

Figure 19 – Illustration of drone types. Source: Windracers, Stock photo

Such dynamics are more akin to ships than aircraft and may present a challenge to conventional onboard tracking systems and, hence, ARAIM and AAIM. Derivations from maritime integrity monitoring algorithms may be more suitable to highly dynamic UAS than conventional aviation algorithms.

The need for absolute positioning: Drone operations may be integrated with conventional air traffic or restricted areas or corridors could be established for drone operations. Currently, as regulations and concepts of operation are still under development, drones operating in the specific or certified categories are restricted to blocks of airspace that are reserved as temporary danger areas (TDAs). This situation is too cumbersome and inflexible to enable drones to operate to their full potential, so much more dynamic reservation of airspace is likely in the future.

Alternatively, some countries, including the UK, are investigating fully integrated airspace where drones and conventional air traffic operate safely in the same airspace blocks at the same time. The following figure illustrates the three potential types of operation.

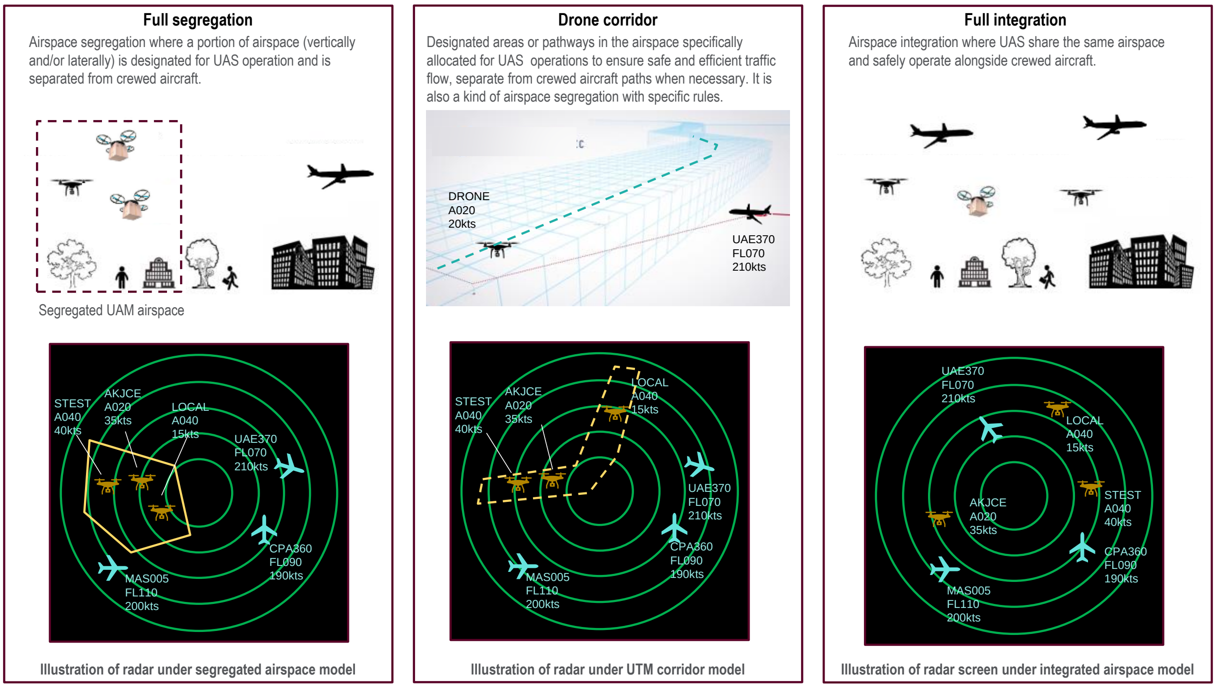

Figure 20 - Concepts for airspace integration between drones and conventional air traffic. Source: ThinkAero

In the first two cases – full segregation and drone corridor – the drone must remain in the designated volume of airspace. Therefore, the drone pilot needs an accurate, reliable and high integrity knowledge of the drone's position.

Electronic conspicuity (EC): is an umbrella term encompassing various technologies that enhance awareness of other aircraft in the same airspace, particularly in uncontrolled (class G) airspace. It aids pilots, UAS and air traffic services by contributing to a situational picture. It is key to the integration of UAS. Currently in the UK air traffic services require EC to be provided using the Mode S secondary surveillance radar (SSR) but there are various other solutions that are or could be used in uncontrolled airspace including ADS-B out, FLARM and Pilot Aware Rosetta. Whilst EC is only compulsory in mandatory airspace, other users have been encouraged to equip their aircraft with EC devices on a voluntary basis.

All EC devices are fed by GNSS position, either internal to the device or from an external, certified source. It is essential, therefore, that the GNSS position is of sufficient accuracy, integrity and availability to support the application.

Detect and avoid (DAA) is the capability to see, sense or detect conflicting traffic or other hazards, such as terrain, pylons and adverse weather, and take the appropriate action to comply with the applicable rules of flight. DAA relies on a combination of sensors and technology – radar, light detection and ranging (LiDAR), infra-red, ultrasonic, the traffic collision avoidance system (TCAS) and automatic dependent surveillance broadcast (ADS-B). The principal position information is likely solely derived from GNSS, which must, therefore, meet highly stringent accuracy, integrity, availability and continuity requirements.

Market size: The 2024 EUSPA market study identifies the scale of the global market for GNSS devices for use in UAS. The results of the analysis are presented in the chart below, showing the market size for four main drone applications. The chart shows that the market size for this sector will be around 10 million units globally by 2033. This is clearly potentially a very large market.

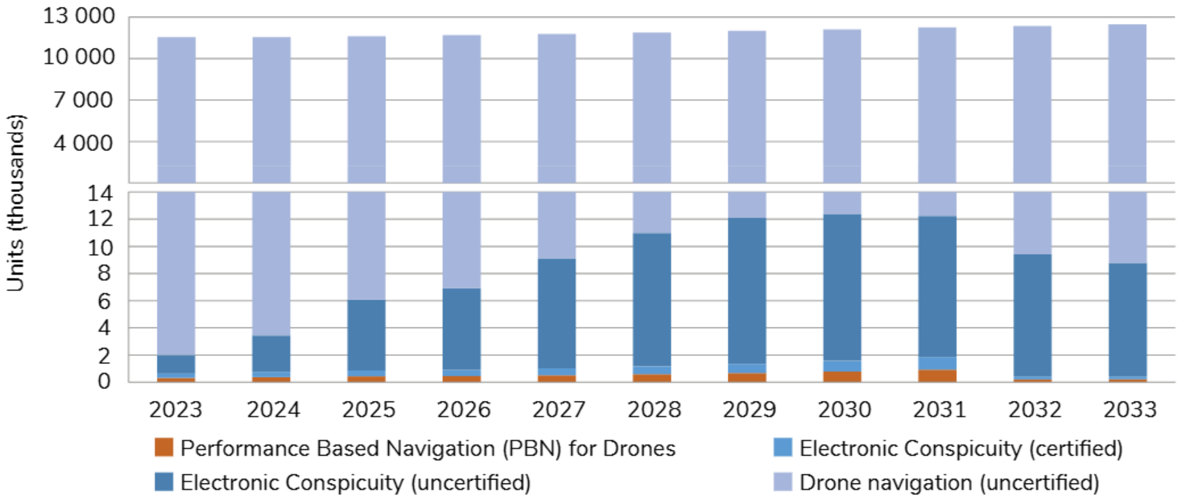

Figure 21 - Market size for drone applications of GNSS devices. Source: EUSPA Market Report 2024

9.1.1.2 Urban air mobility

Urban air mobility (UAM) is a concept to transport passengers and cargo from any location to any destination within an urban area and, also, potentially in rural areas. It usually refers to existing and emerging technologies such as traditional helicopters, vertical take-off and landing aircraft (VTOL), electrically propelled, vertical take-off and landing aircraft (eVTOL), and UAS. These aircraft are characterized as multiple electric-powered rotors or fans for lift and propulsion, along with fly-by-wire systems to control them. Initially UAM vehicles are likely to have crew onboard but eventually may become autonomous. In both cases they will require high accuracy, high integrity absolute positioning.

Figure 22 - Urban Air Mobility concept aircraft. Source: Stock photo

Urban canyons: UAM operations will, by their very name, take place mainly in the urban environment, often operating below the top of the tallest buildings. This means that the line-of-sight to GNSS constellations will be inhibited in so-called urban canyons. There is likely to be a very strong multipath environment as GNSS signals suffer multiple reflections from buildings and the ground. There is also likely to be (out-of-band) electromagnetic interference in the cityscape. This environment has much more in common with ship operations in ports than conventional aircraft operations well above the ground. GNSS processing, including RAIM, will need to be operable in this environment.

The urban canyon environment will also affect the visibility of satellites and, therefore, the capability to perform RAIM processing. The RAIM prediction tool could be extended to operate in the urban environment.

Crowd-sourcing: The likely future high volume and density of UAM vehicles may present an opportunity for crowd-sourced inputs to improve positioning and navigation performance for UAM vehicles. This opportunity may also apply to other UAS and could be extended to ground vehicles in the urban environment.

9.1.1.3 The use of UAS in other sectors

Besides the requirements for safe UAS operation, there are an increasing number of drone applications where higher PNT performance is needed. Such applications include science, agriculture, goods delivery, surveying, offshore exploration and exploitation and search. The PNT requirements for these applications will need to be captured, verified and published as basis for certification of equipment and approval of operations.

9.1.1.4 Conclusions

The rapidly emerging mobility concepts in the aviation sector – UAS and UAM – will require high performance positioning and navigation, for example, to comply with electronic conspicuity requirements, airspace restrictions, and to avoid collisions with each other and other aircraft. The likely operating environment at low level, the high multipath from building and highly dynamic but relatively slow-moving vehicles means that the traditional approach to integrity applied in the aviation sector may not be applicable. This environment is similar to that experienced by ships, especially in ports. Therefore, there is likely an opportunity to extend INSPIRe's integrity concepts to the UAS and UAM sectors.

The M-RAIM and MG-RAIM algorithms developed in the INSPIRe project will likely be more appropriate than conventional ARAIM although they will likely need some development and adaptation. RAIM prediction could be extended to be useful in urban environments, indicating where and when RAIM will and will not be available. Integrity monitoring of EGNOS will enable its use with the potential advantages in performance improvement. The high volume of vehicles will likely facilitate crowd-sourcing in some circumstances.

9.1.2 Highly connected autonomous vehicles

Autonomous road vehicles rely on very accurate, real-time and high-performance positioning available at all times and in all operational environments.

Figure 23 indicates the potential market size across the road vehicles sector according to the EUSPA 2024 market report [22]. By 2033, this shows a potential market size of over 200 million receiver units annually for various use cases across the sector, some of which will have integrity needs.

Specifically, for connected and automated driving (CAD) applications where the need for integrity is critical, the study estimates a potential market size of 9 million units per year by 2033.

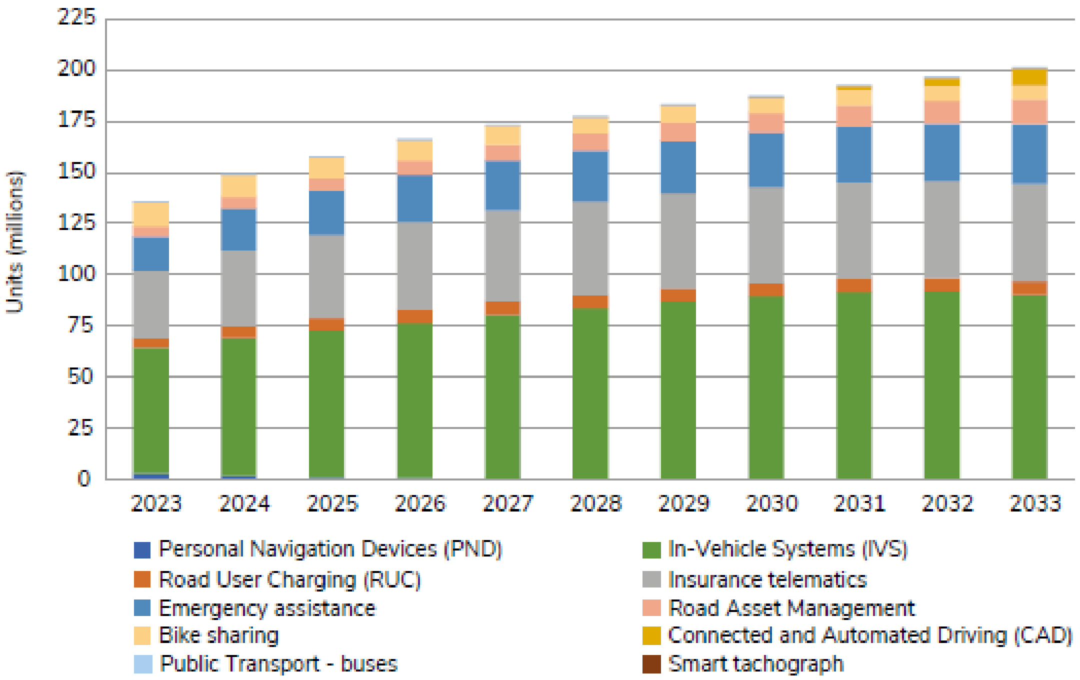

Figure 23 - Market size for connected and automated driving applications of GNSS devices. Source EUSPA Market Report 2024

To achieve the required performance for connected and automated driving applications, data is fused from a variety of sensors – inertial measurement units (IMUs), cameras, radar, LiDAR and GNSS. The need for high accuracy and availability relies on novel correction services offering up to centimetre-level accuracy and wide coverage and availability. Moreover, driven by user needs, captured in the safety-related requirements of the automated driving standards (e.g. ISO 26262), the industry has also started to offer integrity as part of its PNT solution.

The opportunities to extend INSPIRe's concepts to highly connected autonomous vehicles are principally:

- VAIM – to combine all sensors to assure the integrity of the integrated PNT solution;
- M-RAIM – to provide an integrity solution in a high multipath environment;
- RAIM prediction – to provide in-car systems with planning data on whether RAIM is likely to be available for the duration of the journey; and
- Peer-to-peer communications of PNT performance data.

9.1.3 Potential applications for peer-to-peer communications

As discussed in section 8.1.4, the potential opportunities to exploit peer-to-peer communications expand significantly as connectivity between devices increases. This makes peer-to-peer communications a significant opportunity to improve integrity in applications such as autonomous vehicles, robotics, and visually impaired persons (VIP), especially as smart cities evolve to integrate communication among vehicles, pedestrians, and infrastructure.

Two specific cases are considered in this section.

9.1.3.1 Networked air traffic management

Network-enabled air traffic management (ATM), illustrated in the figure below, is a vision for future airspace operations based on data sharing, distributed processing, and end-user applications.

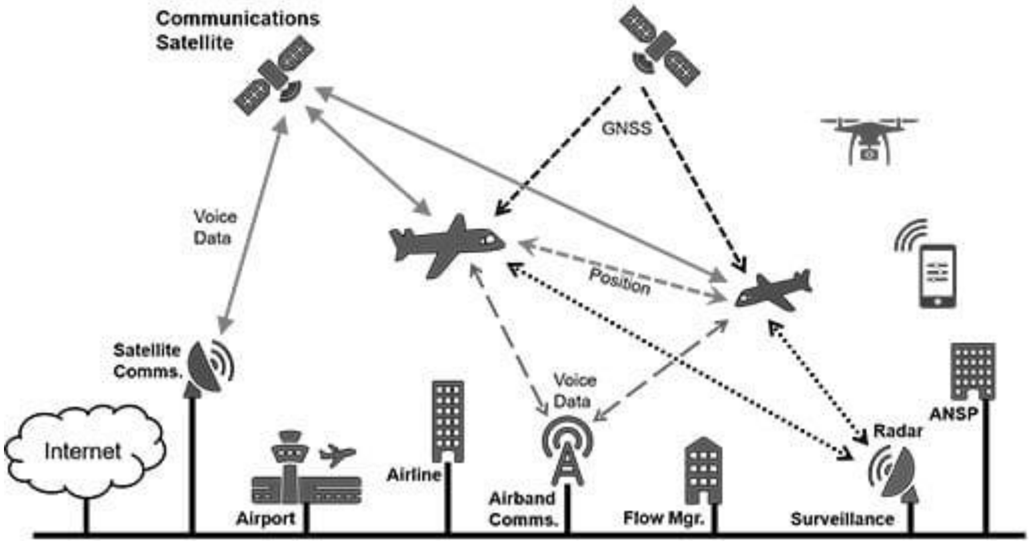

Figure 24 - Network enabled air traffic management. Source: ThinkAero

The idea of the aircraft as a sensor or node in the network is one of the underpinning principles of network-enabled ATM where the original idea was for individual aircraft to provide weather data (which in fact they already do in some areas). This could be extended to the provision of PNT performance data.

9.1.3.2 Continuously operating reference systems (CORS)

System-level crowdsourcing offers opportunities for SBAS providers, including the UK in the future, to utilise CORS networks to improve error characterisation and deliver more reliable and safer distributions to users. In the UK, system-level crowdsourcing can contribute to a robust CORS network with enhanced data update rates and precision.

Specifically, together DFMC and peer-to-peer communications could provide Ordnance Survey (OS) and its commercial partners (Hexagon, Trimble, Topcon, AXIO-NET, SoilEssentials, Premium Positioning) the opportunity to improve the OS Net CORS network's performance to achieve the required level of performance for system-level peer-to-peer communications, including offering enhanced precision and update rates to users.

9.2 Developing standards in other sectors

INSPIRe provides a validated set of requirements which have been translated from user needs. Although the INSPIRe's focus has been to support the development of maritime solutions, PNT is a global industry supporting other global industries. The development of supporting standards should, therefore, follow the normal global approach, not least to ensure that markets for INSPIRe solutions are as wide as possible.

INSPIRe's requirements therefore present an opportunity, either by utilising the general development approach or the requirements themselves, to develop a global approach for deploying standards across sectors. Particularly in comparable sectors where there are also needs for high-integrity positioning with similarly complex local environments.

This section highlights the current status of autonomous aspects of the aviation and road sectors to identify potential opportunities where INSPIRe's requirements may support ongoing development activities.

9.2.1 User needs and requirements

EUSPA in its series of publications on user needs and requirements has collected the PNT requirements for hundreds of applications and use cases. This requirements series forms an excellent starting point for the refinement of requirements for the potential non-maritime INSPIRe applications highlighted in this section. Use of this series avoids having to "*reinvent* *the wheel*" as the requirements have been captured through working groups comprising the key stakeholders from the UK (prior to Brexit) and Europe.

The EUSPA requirements series includes:

- Report on maritime, inland waterways, fisheries and aquaculture. User needs and requirements. 2023.
- Report on aviation user needs and requirements. Outcome of the EUSPA user consultation platform. 2021.
- Report on road user needs and requirements. Outcome of the EUSPA user consultation platform. 2021.
- Report on rail user needs and requirements. Outcome of the EUSPA user consultation platform. 2021.
- Report on location-based services user needs and requirements. Outcome of the EUSPA user consultation platform. 2021.
- Report on surveying user needs and requirements. Outcome of the EUSPA user consultation platform. 2019.

Earlier versions of these studies formed the basis elements of MarRINav's user needs analysis, and hence INSPIRe's, thus demonstrating the continued relevance of these studies as a starting point.

9.2.2 Application to uncrewed aerial systems and urban air mobility

Requirements for UAS and UAM are being developed as part of the standardisation described below.

As introduced above, there are three categories of drone operation in Europe: open, specific and certified. In very simple terms, drones in the open category are restricted to visual line of sight (VLOS) operations where the drone pilot maintains direct visibility to the drones. This type of operation will likely only require a rudimentary PNT solution, if any at all. At the other end of the spectrum, drones operating in the certified category will operate beyond visual line of sight (BVLOS) and are likely to be integrated with conventional air traffic. Their PNT requirements are, therefore, likely to be very similar to those for conventional air traffic.

Those drones operating in the middle ground, in the specific category, will likely operate BVLOS and will require PNT performance commensurate with their concept of operations, not only for navigation but also to support electronic conspicuity and geo-awareness so that the drone operator can comply with airspace restrictions. The requirements for this type of drone operation are in development.

Standards for UAS are under development and are following the normal process for civil aviation. The International Civil Aviation Organization is taking the lead at the global level and will define performance requirements in terms of RNP parameters. These will then be adopted (or exceptions filed) by national regulators.

To do this, ICAO has set up a Remotely Piloted Aircraft Systems Panel (RPASP) to produce draft standards and recommended practices (SARPs) for uncrewed aircraft to facilitate the safe, secure and efficient integration of UAS into non-segregated airspace and aerodromes. The panel recommends RPAS to be equipped and have the required operational approvals in terms of required navigation performance, required communication performance and required surveillance performance as required by the airspace within which they plan to operate. UAS shall also be able to operate in accordance with Instrument Flight Rules and be separated from other air traffic in accordance with the rules applicable to the class of airspace within which they are operating. Similarly, ICAO has established the Advanced Air Mobility Study Group (AAM SG) to support the development of a holistic vision and framework regarding UAM. This is done in a coordinated manner with other ICAO expert groups, as appropriate, with the aim to support a safe, secure, efficient and environmentally sustainable integration of AAM operations, and to facilitate the development of the AAM ecosystem.

40 CAAs worldwide are cooperating as the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) is a cooperation of 40 CAAs worldwide to develop harmonised rules for uncrewed aircraft.

9.2.3 Application to highly connected autonomous vehicles

The requirements for autonomous driving are much more immature than those for maritime and aviation. As stated above, EUSPA has collected some high-level requirements for automated driving – so-called V2X applications – for the PNT solution. These are:

- Availability better than 99.9%;
- Horizontal accuracy better than 20cm; and
- Integrity with a 10 to 15m HPL and integrity risk of 10^{-7}.

These requirements are very general and will require further development and validation.

Standards for road vehicles are produced by various bodies, including:

- The International Standards Organization (ISO), a non-governmental organisation that develops and published standards across many sectors;
- CEN/CENELEC, which are non-governmental organisations that develop European standards with CENELEC focusing on electro-technical matters;
- ETSI, which is the European standards organisation that focuses on information and communications technology (ICT); and
- SAE (formerly the Society of Automotive Engineers) is a global association that develops standards in the aerospace, automotive and commercial vehicle industries.

For connected and autonomous vehicles, a plethora of standards already exist that are relevant to GNSS integrity. It is likely that existing standards will need to be adapted or additional standards will need to be established to enable INSPIRe’s concepts to address this market.

10 CONCLUSION

This report has explored applications of INSPIRe's integrity concepts at both the user-level and at the system-level, and considered how these concepts can be integrated as an integrity architecture.

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 thus:

- 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

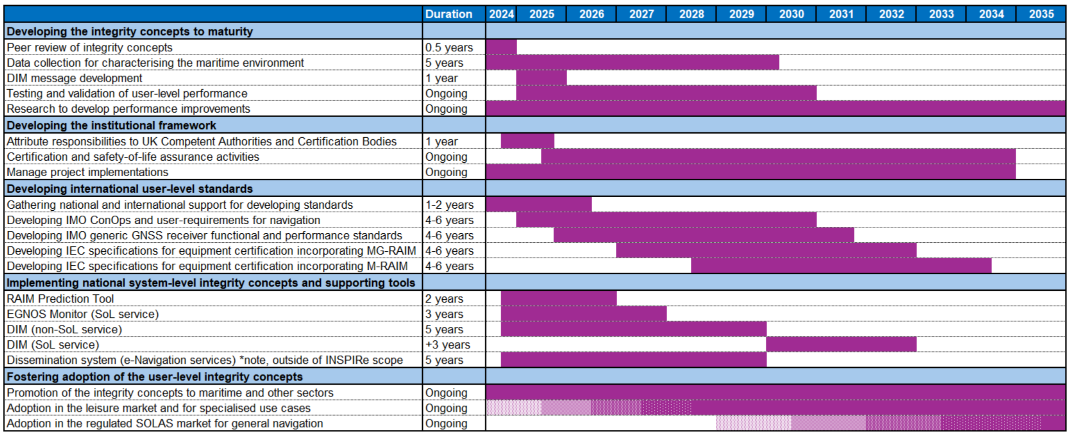

Figure 25 – Indicative implementation roadmap for INSPIRe's integrity architecture

This roadmap includes various dependencies which must be considered, notably including modelling the maritime environment, gathering the industry support required to put forwards international standards, and consultation processes, which may result in uncertainty with the final delivery timelines.

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.