4000126063/18/NL/MP

NAVISP-EL3-001

MarRINav

MARITIME RESILIENCE AND INTEGRITY OF NAVIGATION

Final Report (FR)

25th March 2020

MarRINav is a project delivered on behalf of the European Space Agency

MarRINav – Maritime Resilience and Integrity in Navigation

Final Report

Version	Date	Author	Reason for change
1.0	25.03.20	G Shaw	Formal release

Document Information

Client	ESA
Project Title	MarRINav – Maritime Resilience and Integrity in Navigation 4000126063/18/NL/MP NAVISP-EL3-001
Deliverable Number	FR – Final Report
Report Title	MarRINav Final Report
Report Version	V1.0
Report Version Date	25th March 2020
Lead Author(s)	Name: George Shaw Organisation: GLA Research and Development
Contributing Author(s)	Paul Williams, GLA Mike Fairbanks, Taylor Airey
Project Manager	Richard Greaves richard.greaves@nlaltd.co.uk NLA International Ltd
Circulation	1. Client 2. Project Files
File Name	20 03 25 Final Report MarRINav v1.0.docx
File Location	Googledrive, Dropbox

Executive Summary

This document is the Final Report (FR) of the 'Maritime Resilience and Integrity of Navigation' (MarRINav) Phase 1 project. It is a self-standing report that provides a complete description of all the work done during the study from January 2019 to February 2020, covering the whole scope of the study. As such, it contains a comprehensive introduction of the context, a description of the programme of work and report on the activities performed and the main results achieved.

MarRINav builds on previous work by the General Lighthouse Authorities of the United Kingdom and Ireland (GLA), plus the London Economics report on the UK economic impact of the loss of GNSS and the UK Government's Blackett report on GNSS vulnerabilities. A variety of shipping, ports, applications and operations are included in the investigation, ensuring that the whole diverse ecosystem of maritime and associated activities is represented along the entire shipping logistics chain from ocean to port hinterland.

GNSS have become the principal (and occasionally the only) source of position, navigation and timing (PNT) for ships. On most modern vessels GNSS are deeply integrated within multiple digital systems on the bridge. For example, in portraying the vessel's position and motion on the mariner's Electronic Chart Display and Information System (ECDIS). But many other systems also depend on PNT from GNSS for their position and timing information. These include the current Automatic Identification System (AIS), the future VHF Data Exchange System (VDES) and the whole of the incoming IMO e-Navigation concept. Maritime navigation standards and solutions are evolving to encompass new applications, notably e-Navigation services and marine autonomous systems including maritime autonomous surface ships (MASS). In the future, these must also consider multi-modal integration of applications as goods flow from the sea, through a port, to the hinterland, to support improved safety, efficiency and environmental protection throughout vital logistics supply chains.

Maritime is not only one of the most GNSS-dependent sectors, but also one of those with the greatest awareness of GNSS vulnerabilities and their consequences. Indeed, many of the key studies of GNSS resilience have focussed on maritime use. The two most important PNT performance parameters for critical maritime applications are Integrity (at both system and user level) and Resilience.

The MarRINav Phase 1 project, conducted in the UK national interest, has explored in depth maritime requirements and potential future solutions for Resilience and Integrity (R&I) of maritime PNT, offering capability to protect and augment maritime UK Critical National Infrastructure (CNI). Whilst the primary focus has been shipping, including port operations, potential cross-sector benefits to national precise Timing and land mobility applications have also been recognised. Specific port requirements, especially for land-side operations (e.g. crane movements), vary across UK locations and to reduce complexity the project's analysis has focused on specific Use Cases within a principal scenario of a container vessel approaching port, docking, offloading cargo and its transition through the port. Additionally, MarRINav has

considered the international context for shipping, the global regulatory environment and the need for solutions to be scalable and expandable to other application sectors, countries and regions.

MarRINav has identified feasible and cost-effective technology options within a system-of-systems outline solution architecture to deliver PNT information meeting the performance requirements of maritime users. Preliminary functional and geographic architectures have been described which support the hybridisation and fusion of GNSS: that is, including both terrestrial and space-based radio navigation systems, integrating GNSS with other PNT sources within multi-system, multi-constellation receivers and other user equipment. Important aspects are the inclusion of E-GNSS (Galileo and EGNOS), with the backup terrestrial systems of Enhanced Loran (eLoran) and the Ranging Mode (R-Mode) of the VHF Data Exchange System (VDES), and complemented by the development of a specific Maritime Receiver Autonomous Integrity Monitoring (M-RAIM) algorithm. The hybrid solution will assure the integrity of PNT at both the system and the user level and the continuity and availability of marine navigation even in conditions of GNSS degradation or loss.

MarRINav candidate Resilient PNT systems considered within Work Package 4 work on RPNT architecture and infrastructure included the following:

- eLoran
- VDES R-Mode, subject to technology maturation
- Radar Absolute Positioning, subject to technology maturation
- Satelles (STL), subject to proof of capability
- LOCATA
- ePelorus
- Integration with on-board Dead Reckoning (DR) systems (traditional and inertial DR)

MarRINav also recognises the role of visual techniques for establishing an estimated position fix (EP), and even in this “if all else fails” scenario, electronic systems like the ePelorus can assist in promulgating electronic position fixes to ships’ systems and shore-side services.

It has been established that each of the candidate systems will be integrated, in the IMO’s Multi-System Receiver (MSR), with a Dead Reckoning (DR) system based on Doppler Correlation Speed Log, gyrocompass and IMU. The aim is that the PNT output will be sourced from the DR system, with the various PNT systems calibrating drift and other errors, including GNSS when it is available, with the system falling back to whatever mix of RPNT systems is available when GNSS has been detected to have failed or is being degraded.

An Outline Development Plan, as part of a wider road-mapping exercise, has pointed the way forward to a resilient and high integrity PNT demonstrator and test-bed for the UK. This would be modular and developed incrementally, with physical test bed and simulation test bed elements mutually supporting and de-risking the validation of the overall design before expansion of the PNT CNI solution to national scale.

Contents

Table of Contents

Glossary

AIS	Automatic Identification System
ASF	Additional Secondary Factor
AtoN	Aids-to-Navigation
CBA	Cost Benefit Analysis
CNI	Critical National Infrastructure
COG	Course Over Ground
DFMC	Dual-Frequency Multi-Constellation
DGPS	Differential GPS
DOP	Dilution of Precision
DR	Dead Reckoning
DTED	Digital Terrain Elevation Database
DVL	Doppler Velocity Log
EC	European Commission
ECDIS	Electronic Chart Display and Information System
ED	Emission Delay
EEZ	Exclusive Economic Zone
EGNOS	European Geostationary Navigation Overlay Service
EMS	EGNOS Message Server
ERNP	European Radionavigation Plan
ESA	European Space Agency
GIS	Geographical Information System
GIVE	Grid Ionospheric Vertical Error
GLA	General Lighthouse Authorities of the UK and Ireland
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema (or Global Navigation Satellite System)
GMDSS	Global Maritime Distress and Safety System
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRI	Group Repetition Interval
GSA	European GNSS Agency
HAL	Horizon Alert Limit
HDOP	Horizontal Dilution of Precision
HMI	Hazardously Misleading Information
HPL	Horizontal Protection Level
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IBPL	Isotropy Based Protection Level
ICAO	International Civil Aviation Organisation
ICP	Integrated Carrier Phase
IGP	Ionospheric Grid Point
IEC	International Electrotechnical Commission
IMO	International Maritime Organisation

IMU	Inertial Measurement Unit
INS	Integrated Navigation System
IPP	Ionospheric Pierce Point
ISM	Industrial, Scientific and Medical
LEO	Low-Earth Orbit
LIDAR	Light Detection and Ranging
LOP	Lines of Position
LRIT	Long Range Information and Tracking
M-RAIM	Maritime Receiver Autonomous Integrity Monitoring
MASS	Maritime Autonomous Surface Ships
MCA	Maritime Coastguard Agency
MCP	Maritime Connectivity Platform
MF	Medium Frequency
MFMC	Multi-Frequency Multi-Constellation
MSC	Maritime Safety Committee
MSF	Three letter code designation of the UK National Physical Laboratory's radio time signal broadcast from Anthorn, Cumbria, UK
MSI	Maritime Safety Information Service
MSR	Multi System Receiver
NLOS	Non-line of Sight
NM	nautical mile
NPL	National Physical Laboratory
NTC	National Time Centre
OOW	Officer of the Watch
PNT	Position, Navigation, and Timing
PPP	Precise Point Positioning
PPU	Portable Pilot Unit
PVT	Position Velocity and Time
R&I	Resilience and Integrity
RaDR	Radar Dead Reckoning
RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency
RIMS	Reference and Integrity Monitoring Stations
RNP	Required Navigation Performance
RORO	Roll On Roll Off
RPNT	Resilient Position, Navigation and Timing
SAR	Search and Rescue
SBAS	Space Based Augmentation Systems
SDD	Service Definition Document
SLAM	Simultaneous Location and (Radar-Return) Map
SOA	Service Oriented Architecture
SOG	Speed Over Ground
SOLAS	Safety of Life at Sea
SPP	Single Point Positioning
STL	Satelles Satellite Time and Location
STS	Ship To Ship or Ship To Shore

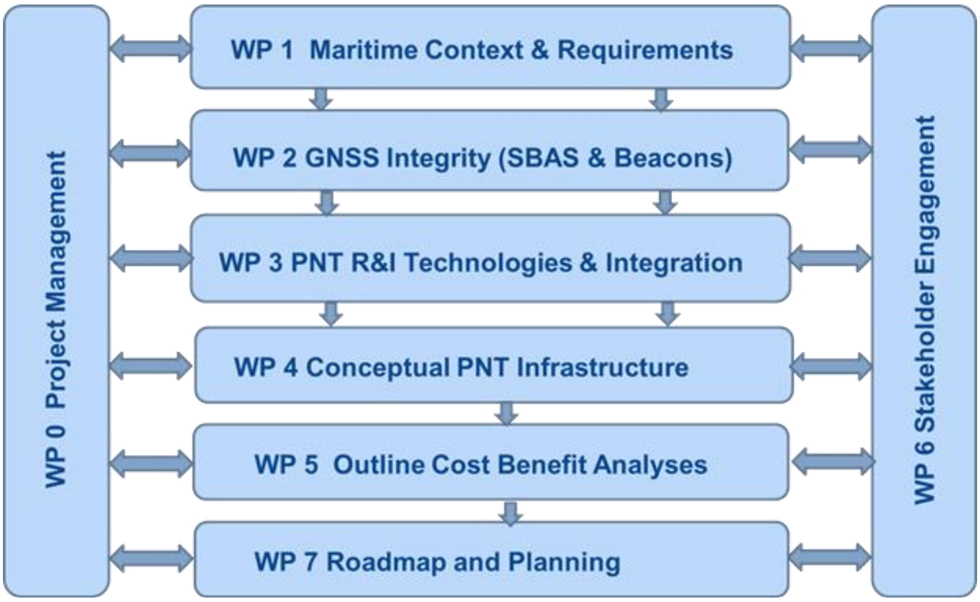
TEU	Twenty-foot Equivalent Units
TOA	Time of Arrival
TS	Terrestrial Segment
TSS	Traffic Separation Scheme
TTA	Time To Alarm
TW	Territorial Waters
TWSTFT	Two Way Satellite Time and Frequency Transfer
UDRE	User Differential Range Error
UIRE	User Ionospehere Range Error
UNOTT	University of Nottingham
US	User Segment
USV	Unmanned Surface Vessel
UTC	Coordinated Universal Time
VDE	VHF Data Exchange
VDES	VHF Data Exchange System
VDR	Voyage Data Recorder
VHF	Very High Frequency
VPN	Virtual Private Network
VTS	Vessel Traffic Services
WAAS	Wide Area Augmentation System
WRC	World Radiocommunication Conference
WWRNS	World-Wide Radionavigation System

1 Introduction

This document is the Final Report of the MarRINav Phase 1 project, summarising the content of all technical reports. The purpose of MarRINav is:

Building resilience & integrity into UK critical national infrastructure for maritime navigation, aids to navigation infrastructure and services at sea and in ports

The MarRINav Phase 1 project successfully completed the following work packages:



The results of this report inform a wide range of stakeholders, including:

- UK Government, Deputy National security Adviser, Department for Transport and UK Space Agency, in respect of inputs to the PNT Strategy, PNT Current and Future Technology and Threats and Hazards Groups convened during Q1 of 2020.
- ESA and GSA, in respect of the EGNOS v2 maritime A.1046 service for integrity at system level and a possible EGNOS v3 service offering integrity at user level.

MarRINav concludes with the following overall recommendations:

1. Create a wide-reaching consensus for the future development of a resilient and high-integrity PNT system-of-systems, meeting the needs of the future UK CNI.

2. Identify an appropriate source of funding to enable the MarRINav project to be progressed to Phase 2, to build on the conceptual solution, adding design detail, and undertake field-scale proof-of-concept demonstration.

3. Engage further with legislators, regulators, standards agencies, industry bodies and manufacturers.

2 Context for maritime resilient high-integrity PNT

The collation of maritime requirements and context for the use of Position, Navigation and Timing (PNT) information is based on formal requirements for navigation performance and an analysis of trends in maritime operations. There are many evolving uses of PNT information within all phases of the voyage from oceanic and coastal navigation to manoeuvres in ports and the port's land-side handling of cargo. The integrity and resilience of PNT data are fundamental to the safe and efficient operations in the end-to-end sea & land logistics chain, underpinning situational awareness and coordinated decision support, future e-Navigation services and the gradual introduction of Marine Autonomous Surface Ships (MASS). The contextual analysis (q.v. Section 2.1) has considered the provision of future maritime Critical National Infrastructure (CNI) of resilient and high-integrity PNT capability in the timeframe of 2030.

In regard to performance level requirements the focus is on the four commonly used and interdependent (as Figure 1) Required Navigation Performance (RNP) parameters: ***accuracy***, ***integrity***, ***availability*** and ***continuity***; and each of these terms is defined from a maritime perspective (q.v. Section 2.2) [1] [2]. Two important PNT performance parameters for critical maritime applications are **Integrity** (at the user level) and **Resilience**. While Integrity is rather well defined (by reference to an "alert limit" and a "confidence interval"), resilience is not.

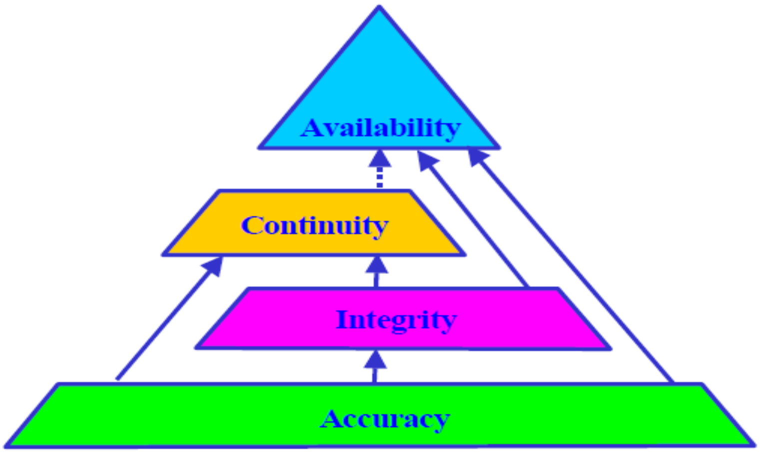


Figure 1: Interdependence of RNP parameters. *Source:* [3]

2.1 Contextual analysis for Resilience and Integrity in PNT Provision

GNSS has become the principal (and often the only) aid to navigation for ships. It is not, however, a system solely used for plotting the ship's location on an electronic chart. An oft-quoted paraphrase that "*any mariner worth his salt should be able to navigate without GPS"* is somewhat misplaced when talking within the context of a modern vessel.

On most large modern vessels GNSS is integrated deeply within multiple digital systems on the bridge and wider ship's systems, not only in portraying the vessel's position and motion on the screen of the Electronic Chart Display and Information System (ECDIS). Other systems aboard ship, and ashore, present and future, depend on the provision of automatic, electronic position, navigation and timing solutions derived from GNSS.

Unfortunately, all GNSS are vulnerable to unintentional RF interference, solar weather events, intentional jamming and spoofing because of their low received signal strength and their need to share the same radio frequency bands. Jamming trials at sea have demonstrated the complete failure of multiple systems aboard ships when GNSS is denied, creating numerous alarms from the various systems whose GNSS input is affected [4]. A more insidious effect occurs when a GNSS receiver is interfered with so that it delivers hazardously misleading information (HMI) – positioning information that is incorrect, it is not obvious that it is incorrect and the mariner is not informed that it is incorrect. Not only does this have a serious impact on safety, but it may have extremely costly implications for the flow of goods, including potential economic loss and environmental damage.

Traffic complexity and density is increasing in many areas. Figure 2 shows an example of the traffic traversing the Dover Straits in the summer of 2018.

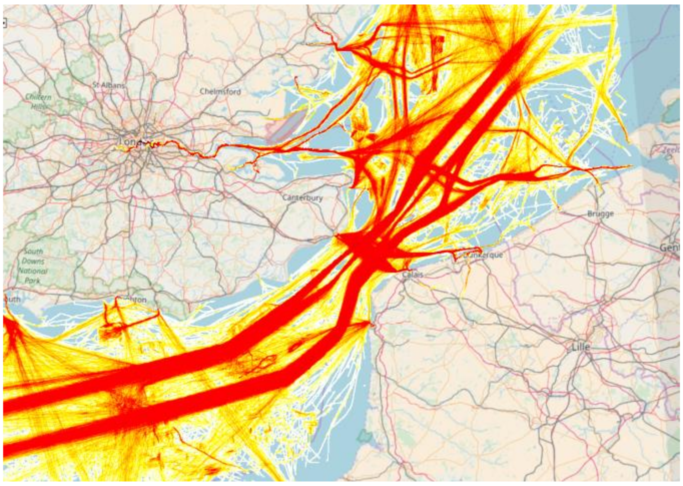


Figure 2: Example traffic density in the region of the southern North Sea, Dover Strait, and Eastern part of the English Channel. ***Courtesy Trinity House, Director of Navigational Requirements, ANATEC analysis of 28 days' worth of AIS data.***

Not only does Figure 2 show the complexity of the traffic, with many crossing and convergence points, it also shows how well-defined and dense the ships' tracks have become (darker lines equate to more vessels). Vessels follow the most economically advantageous route, taking distance, weather and other factors into account. Often this route is also the least environmentally damaging as it is based on minimum fuel burn, for financial reasons. This means that the majority of vessels are concentrated on the same track with little lateral divergence. In busy areas of dense track, vessels will also follow each other closely; in the Dover Straits, for example, the spacing between vessels has reduced to very low margins, placing greater reliance on accurate navigation and automated systems to avoid collisions.

Offshore wind generation capacity has increased by a factor of eight around the UK over the past 10 years. Figure 3 shows the location of actual and planned wind farms, many of which can be seen to be in areas of high traffic density, further increasing traffic complexity and affecting navigation requirements. Although not increasing at the same rate as offshore renewables, there is a considerable amount of oil and gas related infrastructure situated in the North Sea, again sometimes interacting with high density shipping lanes.

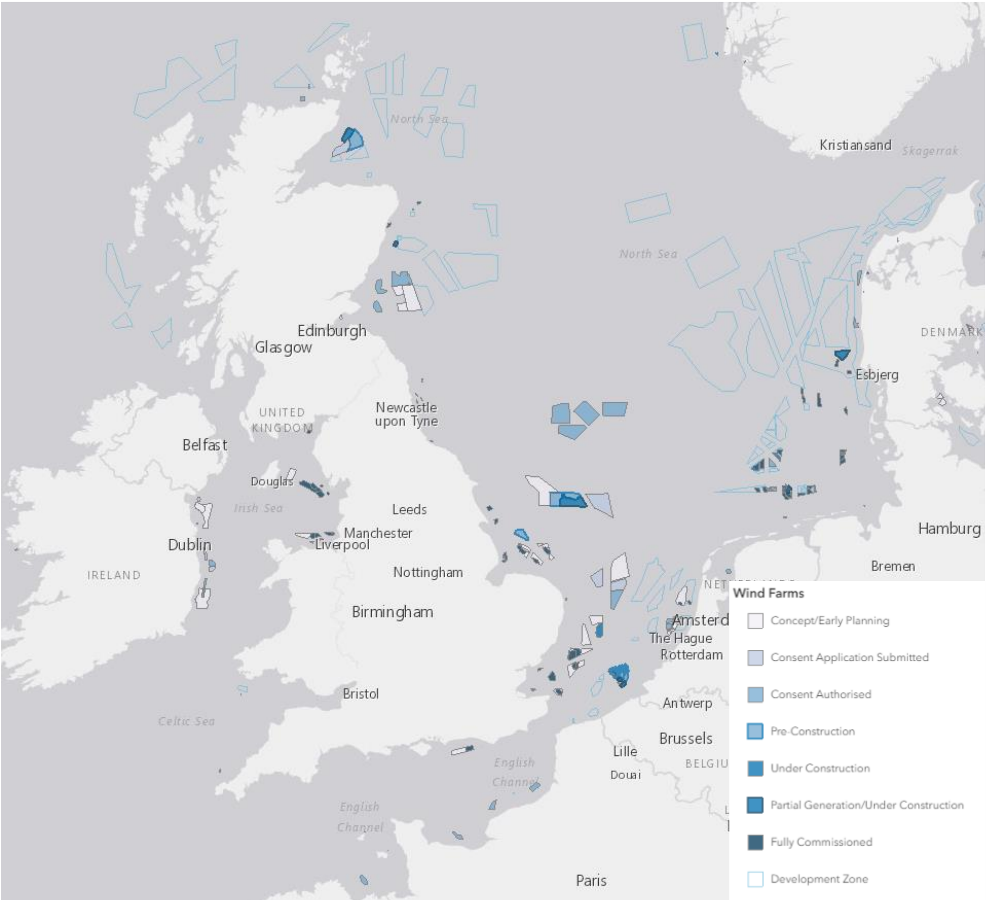
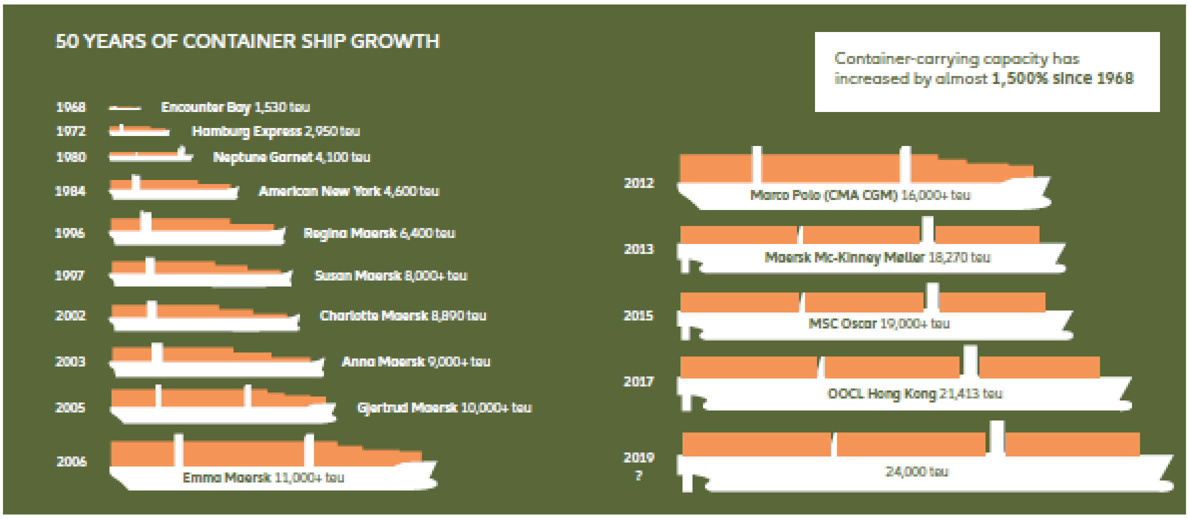


Figure 3: Actual and planned offshore wind generation [5].

Currently 95% of goods are transported by sea, and trends in the maritime sector are driving change in navigation requirements. Ship size is increasing, for example, the container vessel *OOCL Hong Kong* (Figure 4) has a capacity of 21,413 twenty-foot equivalent units (TEU), is approximately 400 m long and 60 m wide. On average, the size of container vessels has increased by 32% since 2011. Over the same period, the average increase in size of tankers and bulk carriers has been 30% and 11% respectively. Figure 4 also illustrates the increase in size in container ships over the past 50 years.

It is thought this increase in ship size, together with a larger global fleet, will result in a doubling of seaborne trade by 2030. With reduced sea-space, as outlined above, there will likely be an increase in the need for management of sea traffic, and the associated requirement for resilient and high integrity position reporting.



Source: Allianz Global Corporate and Specialty, Safety and Shipping Review, 2018. [6]

Figure 4: The evolution of container ship size over the last 50 years, diagram shows largest single ship capacity in each year.

2.1.1 The e-Navigation System-of-Systems

The IMO has recognised the need for Resilient PNT to support e-Navigation. Resilient PNT will be a core pillar of the future e-Navigation system-of-systems, as illustrated in Figure 5.

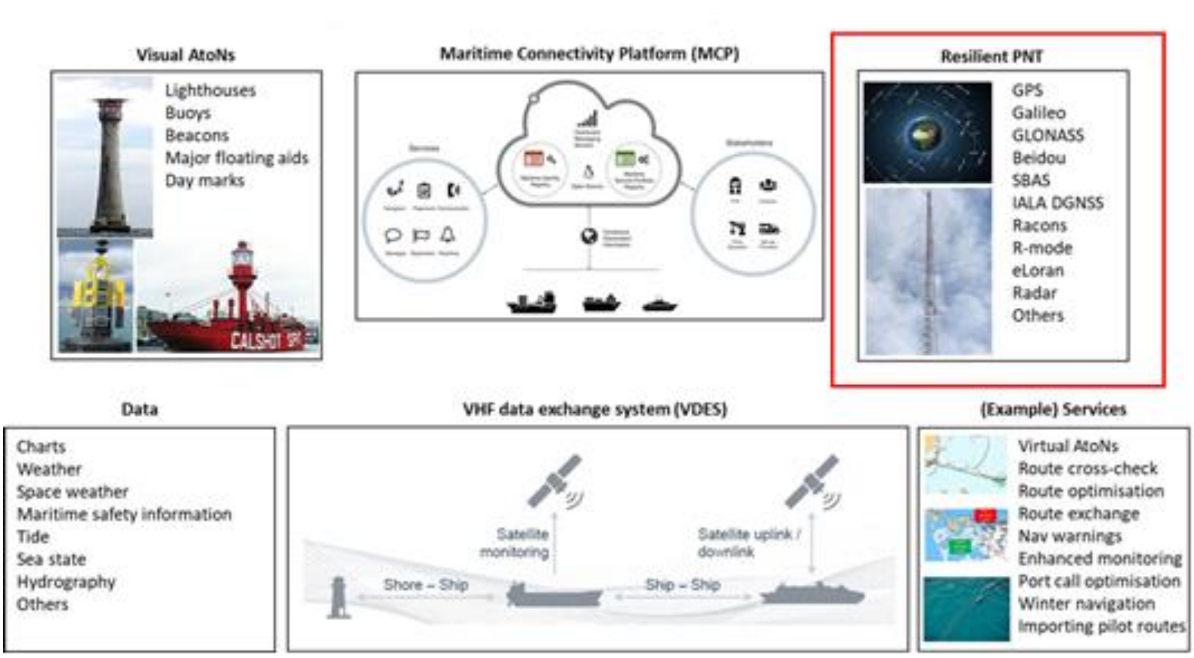


Figure 5: The e-Navigation system-of-systems.

This system-of-systems comprises traditional **visual AtoN**, such as lighthouses, buoys, beacons, etc.; the Maritime Connectivity Platform (**MCP**), the functions of which include maritime actor identity authentication and certification, service registration and location, in addition to the provision of an optional resilient data communications conduit; **Resilient PNT** based on core dual-frequency multi-constellation (DFMC) GNSS, GNSS augmentation and terrestrial, complementary, back-up systems; the VHF Data Exchange System (**VDES**) and **data** supporting services.

2.2 Definitions

2.2.1 Integrity

The IMO defines integrity as: *The ability to provide users with warnings within a specified time when the system should not be used for navigation.* Integrity is provided through *integrity monitoring*, which is the process of determining whether the system performance (or individual observations) allows use for navigation purposes. Integrity may be described by three parameters:

1. The *threshold value* (or alert limit) – the maximum allowable error in the measured position - during integrity monitoring – before an alarm is triggered.

2. The *time to alarm* – the time elapsed between the occurrence of a failure in the system and its presentation to the user (the mariner on the bridge).

3. The *integrity risk* - the probability that a user will experience a position error larger than the threshold value without an alarm being raised within the specified time to alarm at any instant of time at any location in the coverage area of the service.

The concept of user-level integrity is that responsibility for determining the validity of a position-solution lies also with the user's navigation receiver, not just the system. The level of position error considered intolerable is called the Horizontal Alert Limit (HAL). Each operation or application would have its own HAL requirement. The receiver is tasked with issuing an alert to the user should it determine that there is the possibility of a position fix with a position error that exceeds the HAL. The receiver thus presents to the mariner a **yes** or **no** decision as to whether the navigation system can be trusted at any position fix. If ever the algorithm determines that a fix should not be used, an alert should be issued to the user. Any fix for which the actual error exceeds the HAL, but is still declared usable, is referred to as Hazardously Misleading Information (HMI). The *integrity risk* requirement specifies a maximum probability of HMI over a nominal time-frame in order to limit the possibility of the equipment misleading the user.

2.2.2 Continuity

Continuity is the probability that a user will be able to determine a navigation solution with specified accuracy and is able to monitor the integrity of the determined solution over the (short) time interval applicable for a particular operation, given that the solution is available at the start of the period. The original IMO definition assumes a fault-free receiver, however, for the sake of resilience, it is necessary to take into account knowledge of the probability of receiver faults when apportioning continuity budgets across the system. An integrity alarm, whether true or false, is a continuity failure. When considering the assignment of continuity and integrity risk budgets to the various components of a navigation system it is important to understand that continuity and integrity are interlinked; they are not separate parameters and one RNP requirement cannot in fact be assigned to an application in isolation from the other.

Continuity and Integrity are deeply intertwined – the requirements and the statistical processes that define them need to be mutually compatible. The navigation-solution is considered usable only if accompanied by the green-light integrity guarantee. Mariners wish to see the green-light preserved for a long enough time to allow them to do their job safely. A stipulation is made that the probability of losing the green-light each epoch is kept to a very low figure to maximise the usability of the system – thus maximising continuity. The probability of a switch to the red-light condition each epoch has to be quite precisely controlled by the receiver to preserve user-level continuity.

2.2.3 Resilience

Resilience is defined as: ***The ability to anticipate, mitigate and recover from disruption.*** From a maritime perspective the activities of r**esilience** include:

1. The provision of a ***user-level integrity*** guarantee, which makes a position solution robust to any arbitrary fault, or disruption, likely to occur in the real world, e.g. cyber threat, space weather, deliberate jamming.

2. The provision of sufficient hold-over capability from alternative systems and sensors that the ***continuity*** guarantee is not undermined by loss of GNSS, for example due to an integrity-alert, jamming or interference.

Resilience is closely linked with user-level integrity issues. These can include such things as local interference and jamming, the effects of multipath signals, non-line of sight propagation; effects that cause bias errors on the pseudorange measurements made by the user's receiver. Should there be such user-level effects (and for that matter system-level effects), we would expect the receiver to inform the user about the problem, perhaps take some action to remove faulty measurements from the navigation solution, and ensure resilience by fail over to an alternative navigation system such as terrestrial PNT transmissions.

2.3 IMO and IALA requirements and context

2.3.1 PNT performance requirements

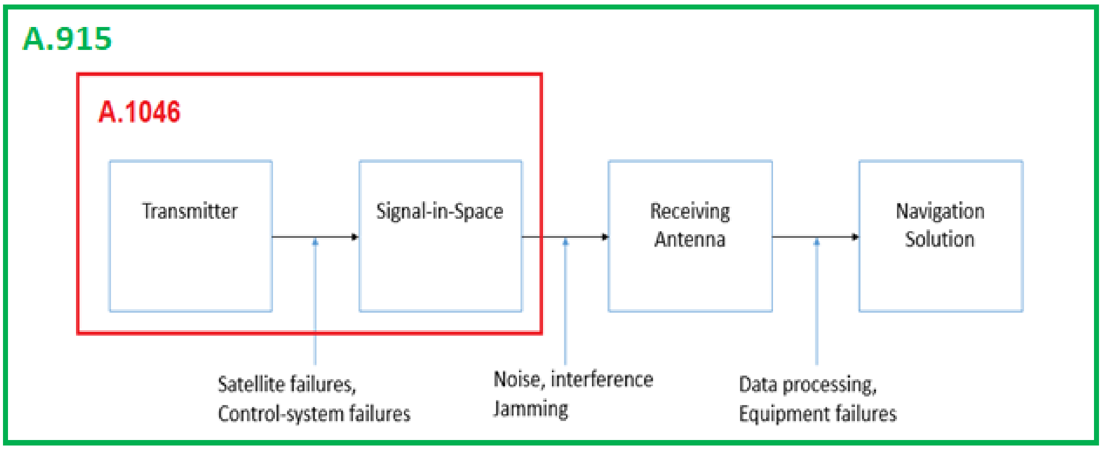


Figure 6: Relationship of IMO A.1046 and A.915 requirements.

Figure 6 depicts the relationship of formal IMO requirements for maritime PNT. System-level requirements, those applicable for recognition of GNSS within the World Wide Radio Navigation System (WWRNS), are stated in IMO Resolution A.1046 and the user-level is considered in Resolution A.915. The A.1046 requirements for PNT system-level performance are shown in Table 1 and the A.915 requirements for PNT user-level performance during General Navigation are shown in Table 2.

Voyage Phase	Accuracy	Continuity	Integrity (TTA)	Availability	Update Interval
Ocean Water	100m (95%)	N/A	As soon as possible	99.8% (signal)	2 s
Harbour Entrances, Approaches and Coastal Waters	10m (95%)	≥99.97% (15 mins)	10s	99.8% (signal)	2s

Table 1: IMO Resolution A.1046 RNP requirements.

Table of the minimum maritime user requirements for general navigation

	System level parameters				Service level parameters			
	Absolute Accuracy	Integrity			Availability % per 30 days	Continuity % over 3 hours	Coverage	Fix interval[2] (seconds)
	Horizontal (metres)	Alert limit (metres)	Time to alarm[2] (seconds)	Integrity risk (per 3 hours)				
Ocean	10	25	10	10^{-5}	99.8	N/A[1]	Global	1
Coastal	10	25	10	10^{-5}	99.8	N/A[1]	Global	1
Port approach and restricted waters	10	25	10	10^{-5}	99.8	99.97	Regional	1
Port	1	2.5	10	10^{-5}	99.8	99.97	Local	1
Inland waterways	10	25	10	10^{-5}	99.8	99.97	Regional	1

Notes: 1: Continuity is not relevant to ocean and coastal navigation.
2: More stringent requirements may be necessary for ships operating above 30 knots.

Table 2: IMO Resolution A.1046 RNP requirements.

2.3.2 Multi System Receiver

Recognising the essential need for resilient PNT in e-Navigation, the recent IMO performance standard for vessels' multi-system, multi-constellation radionavigation receivers (MSR) supports the use of European GNSS (e.g. Galileo and EGNOS) alongside other GNSS components of the World-Wide Radio Navigation System (WWRNS), augmentation and terrestrial PNT sources [7]. The IMO MSR guidelines propose this as the way to achieve the resilience and integrity of PNT required by ships' systems [8]. As shown in Figure 7, the basic principle of the MSR is to use all available signals, not only GNSS but also augmentations and terrestrial transmissions. The MSR concept consists of a sensor layer and a processing layer, the output of which contains Position Velocity and Time information, AND integrity and status data. This data output can also be integrated as part of the ensemble of other ships' sensor systems (gyrocompass, speed logs, etc.) within PNT Data Processing software running on the main bridge display (ECDIS), RADAR or Integrated Navigation System (INS) (Figure 8). The concept of the MSR platform forms the basis of considerations for the integration of the ship-borne components of the Resilient PNT systems explored within MarRINav.

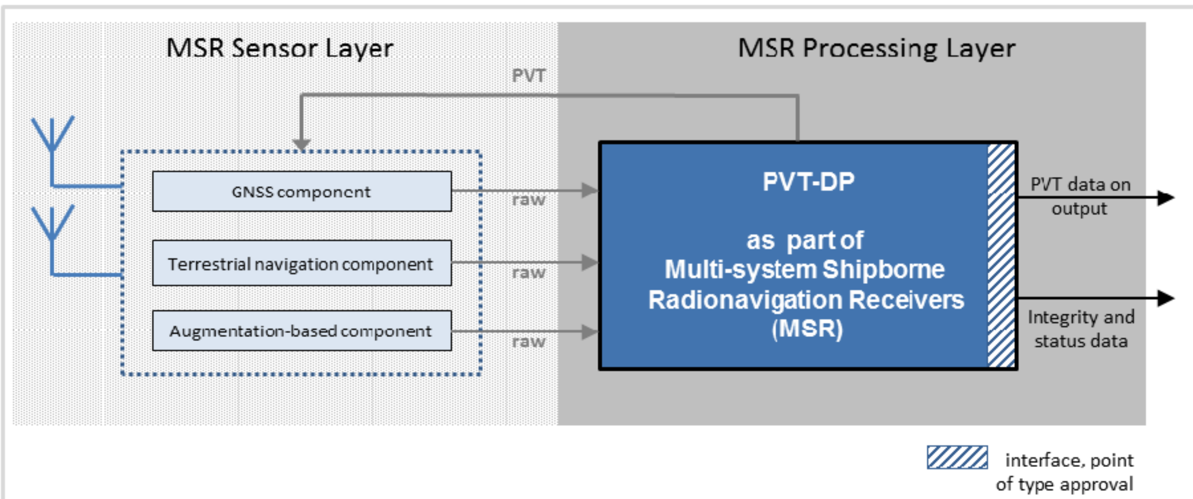


Figure 7: The IMO's proposed Multi-system Radionavigation Receiver architecture.

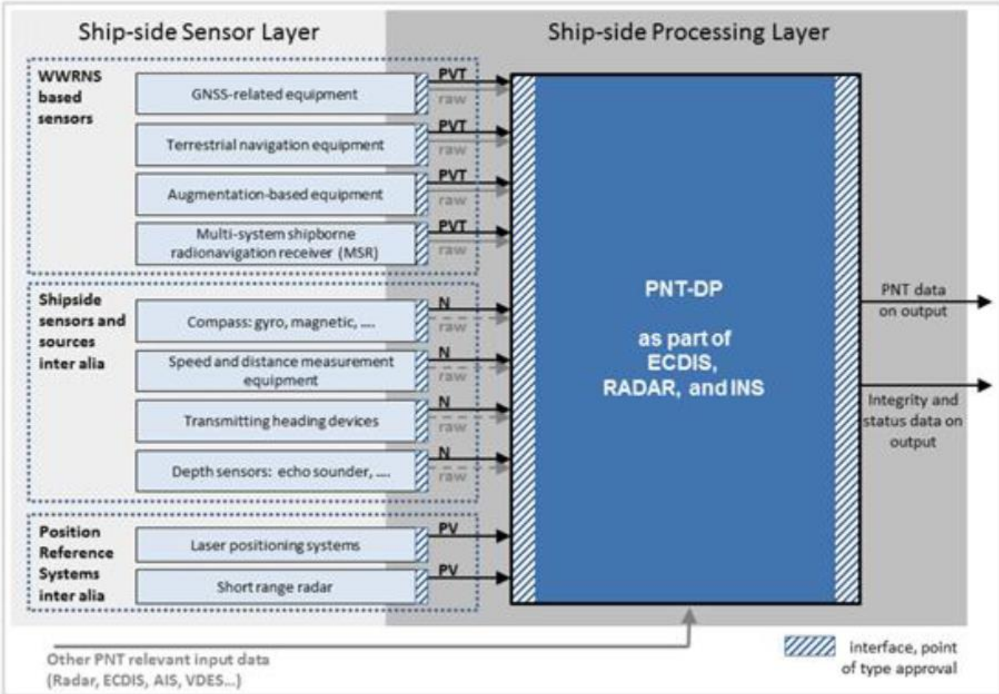


Figure 8: Proposed architecture of PNT Data Processing (PNT-DP) integrated as software into the Integrated navigation System, ECDIS or RADAR aboard ship.

2.3.3 IALA Recommendation R-129

IALA produced Recommendation R-129 [9] on '*GNSS Vulnerability and Mitigation Measures' in December 2008;* and is now 11 years old. IALA state that:

"*in addressing the issue of position fixing, it can be defined as accurate and reliable electronic position, navigation and timing signals, with 'fail-safe' performance (probably provided through multiple redundancy, e.g. GNSS, differential transmitters, eLoran and defaulting receivers or onboard inertial navigation devices".*

Further, IALA recommends that:

"*National Members and other appropriate Authorities maintain and develop backup and contingency aids to navigation, which may include radio aids to navigation and conventional aids to navigation, appropriate to the identified level of risk."*

IALA defines alternative navigation systems as able to provide PNT support at various levels:

- A **redundant** system provides the same functionality as the primary system, allowing a seamless transition with no change in procedures;

- A **backup** system ensures continuation of the navigation application, but not necessarily with the full functionality of the primary system and may necessitate some change in procedures by the user;
- A **contingency** system allows safe completion of a manoeuvre, but may not be adequate for long-term use.

MarRINav has given careful consideration to RPNT systems as being **redundant**, **backup** or **contingency;** however any resulting RPNT solution will likely be a hybrid mix of systems.

2.4 Geographic Coverage and Scenario

MarRINav has investigated a proposed architecture for the provision of resilience and integrity in and around UK and Irish coastal waters. Coverage performance of various resilient PNT systems is important in relation to the geographical region of operation and locations where risk of collision or grounding of a vessel is particularly high.

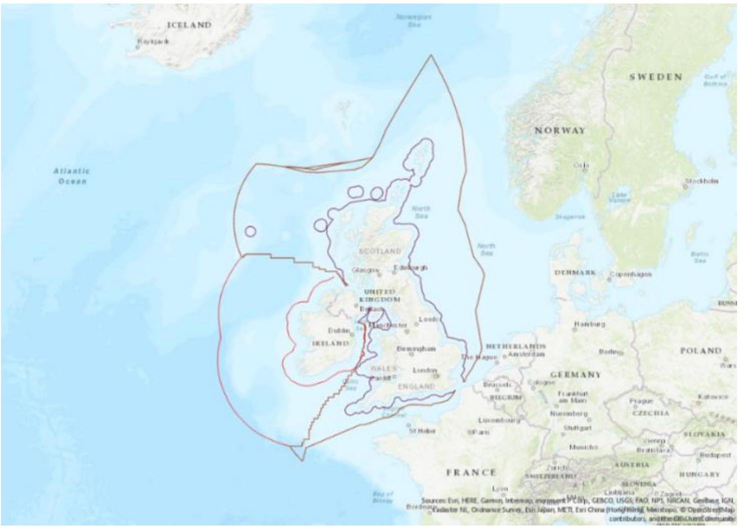


Figure 9: Extent of the UK and Irish maritime administrative boundaries; territorial waters and Exclusive Economic Zones.

Figure 9 indicates the limits of the Exclusive Economic Zones (EEZ), and territorial waters of the UK and Ireland. MarRINav has explored options for the provision of RPNT systems to the extremes of the EEZs. The software Geographical Information System (GIS) ArcGIS™ has been used to collate and analyse the performance of each system with respect to these regions, and locations of various Blue Economy applications, including General Navigation.

A specific scenario linking a sequence of Use Cases was selected for analysis. The scenario follows the progression of a container ship and its cargo from oceanic voyage phase, through docking, to cargo being unloaded, stacked and transported to the port gate. The scenario is depicted in Figure 10.

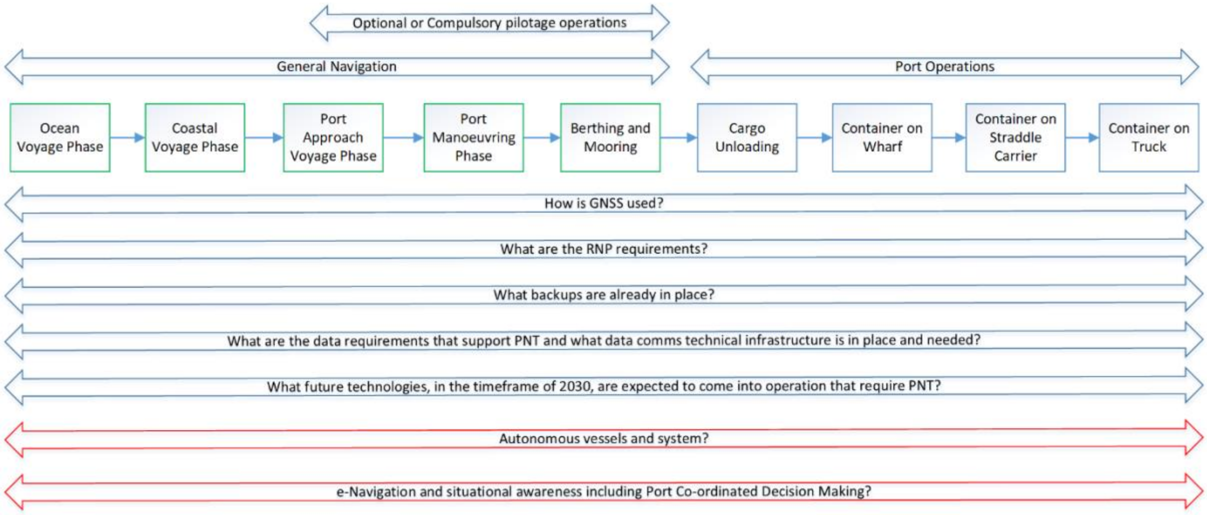


Figure 10: Scenario of linked Use Cases for maritime analysis.

3 EGNOS v2 maritime PNT system-level integrity

An analysis of EGNOS V2 capability for maritime performance was conducted, primarily with the aim of investigating the accuracy, availability and continuity of SBAS augmented GNSS solutions within the western extremities of the UK and Irish EEZs. These sea areas are in the outermost expected coverage of the EGNOS v2 service area, but are generally not heavily trafficked. This is not to put into question the undoubted benefits of a future maritime EGNOS 'A.1046 service' for integrity at system-level, which will provide extensive coverage of the EEZs, but to investigate the western limits of possible service coverage. A subsidiary aim was to determine, if GLA DGPS beacons were to be discontinued in favour of EGNOS, whether the retention of one or more IALA DGPS beacons in the west of Ireland or Scotland would support the coverage at the western edge of the EEZs.

To address these questions, a number of simulations, using the Iguassu SBAS Simulator Version 2 (SSv2), have been performed. To ensure that the results from SSv2 are realistic, an extensive test and calibration exercise was carried out prior to this work. The result of this exercise was a configuration for SSv2 which enables performance predictions that statistically match the real performance of EGNOS as determined from the post-processing of sample data sets.

With a properly calibrated and configured simulation tool, performance simulations have been performed to assess whether EGNOS meets the maritime requirement for availability of 10m (95%) at western EEZ locations. Assessment of continuity has not been performed due to the limitations of a deterministic simulation and a 24-hour constellation repeat period. Continuity is closely related to availability: any occurrence of a predicted positioning error of greater than 10m is an 'availability event', which in turn would trigger 'continuity events'. A single availability event in a 24-hour simulation will affect a 15-minute continuity requirement for at least 15/(24*60) = 1% of the time, hence exceeding the 99.97% continuity requirement. This analysis has therefore not attempted to determine continuity from the accuracy statistics, but has identified various availability events and has then attempted to determine the origins of these events.

3.1 Availability event analysis by simulation

An event of particular interest was found at Stornoway (STOR) on day 075 of 2018, depicted in Figure 11. The event was observed to repeat each day, reflecting the fact that the GPS constellation advances by 4 minutes per day. The analysis has found that the identified availability events are not caused by either the geometrical weakness of the GPS constellation (represented through DOP) nor the exclusion of satellites from the EGNOS positioning solution due to weaker RIMS tracking towards edge of coverage. The most likely cause of the availability events appears to be the exclusion of satellite measurements from the positioning solution due to a lack of ionospheric corrections from the EGNOS ionospheric grid.

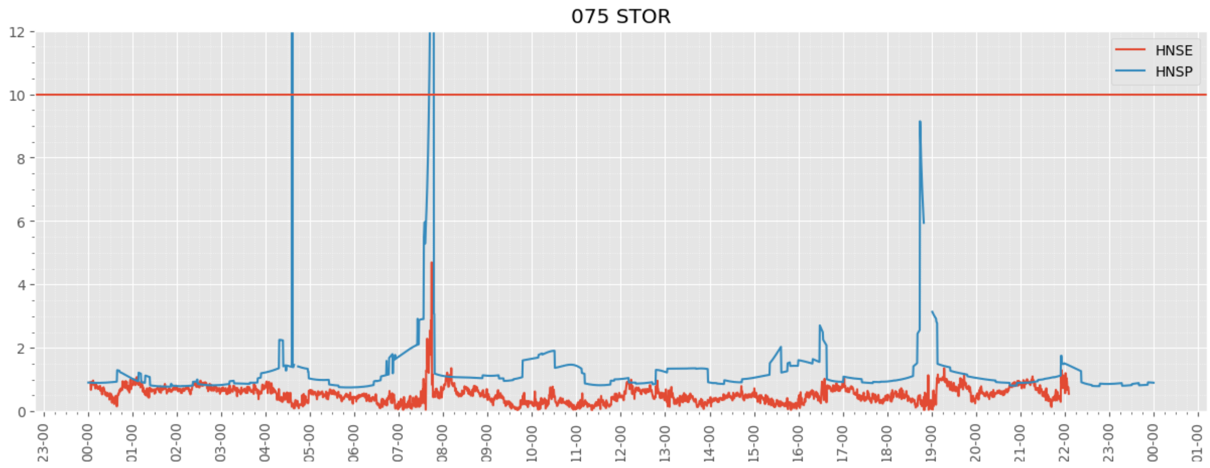


Figure 11: 95% accuracy plot for STOR on 16/03/19.

Since EGNOS is currently a service that caters for single frequency receivers, users are required to correct their single frequency measurements using an ionospheric correction interpolated from a grid of points (Ionospheric Grid Points, or IGPs) that is determined by the RIMS network and broadcast as part of the EGNOS data message. If a user's measurement passes through a part of the ionospheric grid that is not adequately monitored by the EGNOS RIMS network, then no correction is possible, and the affected measurement must be excluded from the positioning solution. This will result in poorer DOP and probably a poorer positioning solution. The analysis has identified, through simulation and processing of historical data, a case that appears to repeat each day (appearing 4 minutes earlier each time).

Monitoring of the EGNOS ionospheric grid relies on a dense distribution of ionospheric pierce points (IPPs) generated by the RIMS network. A dense network of RIMS locations, each generating a scatter of IPPs within a certain elevation-dependent radius of the RIMS location, will produce a dense scatter of IPPs throughout the coverage area. On the periphery of the RIMS network the density of the IPPs generated by the RIMS network will decrease, to the point that grid points beyond this coverage area will not be adequately monitored. However, it is still possible that users' measurements in the western area of the EEZs will pass through these inadequately monitored parts of the network and will consequently have to be excluded from the positioning solution.

Having identified this as the likely cause of the availability events, the analysis addressed whether the use of IALA beacons can mitigate these availability events, i.e. whether they can keep the accuracy to better than 10m. An alternative approach was also investigated to examine whether the inclusion of additional RIMS locations (possibly close to the infrastructure of the existing DGPS beacon sites) could otherwise solve the inadequate monitoring of the ionospheric grid.

The analysis has shown that the spike in performance is present also in the DGPS positioning results. This was an unexpected result and needs further investigation. However, the spike in DGPS performance is below the 10m accuracy requirement, suggesting that DGPS can indeed provide the required accuracy even at a significant distance (several hundred km) from the beacon.

Analysis of the inclusion of additional RIMS locations has proven to be particularly effective at improving the monitoring of the EGNOS ionospheric grid, to the point that a few, e.g. three, additional RIMS in the UK would fill those holes in the ionospheric grid that were observed in these analyses.

3.2 Actual performance availability event analysis

In addition to the repeating spike in predicted performance, testing also revealed a case where a spike above 10m in the actual performance was not predicted by the 95% performance prediction. Whilst this single event was within the 5% of the statistically expected cases, a brief investigation revealed that this seems to have been caused by a combination of a reduced number of available satellites (above a 15˚ elevation mask) and the probable down-weighting of one or more satellites due to EGNOS model weighting. The nature and cause of the down-weighting remains to be explored.

In the following example we consider the impact on a user at the approximate western limit of the Irish EEZ, at 55˚N, 15˚W, for which the ionosphere visibility of monitored (green dot) and unmonitored (black cross) IGPs is illustrated in Figure 12.

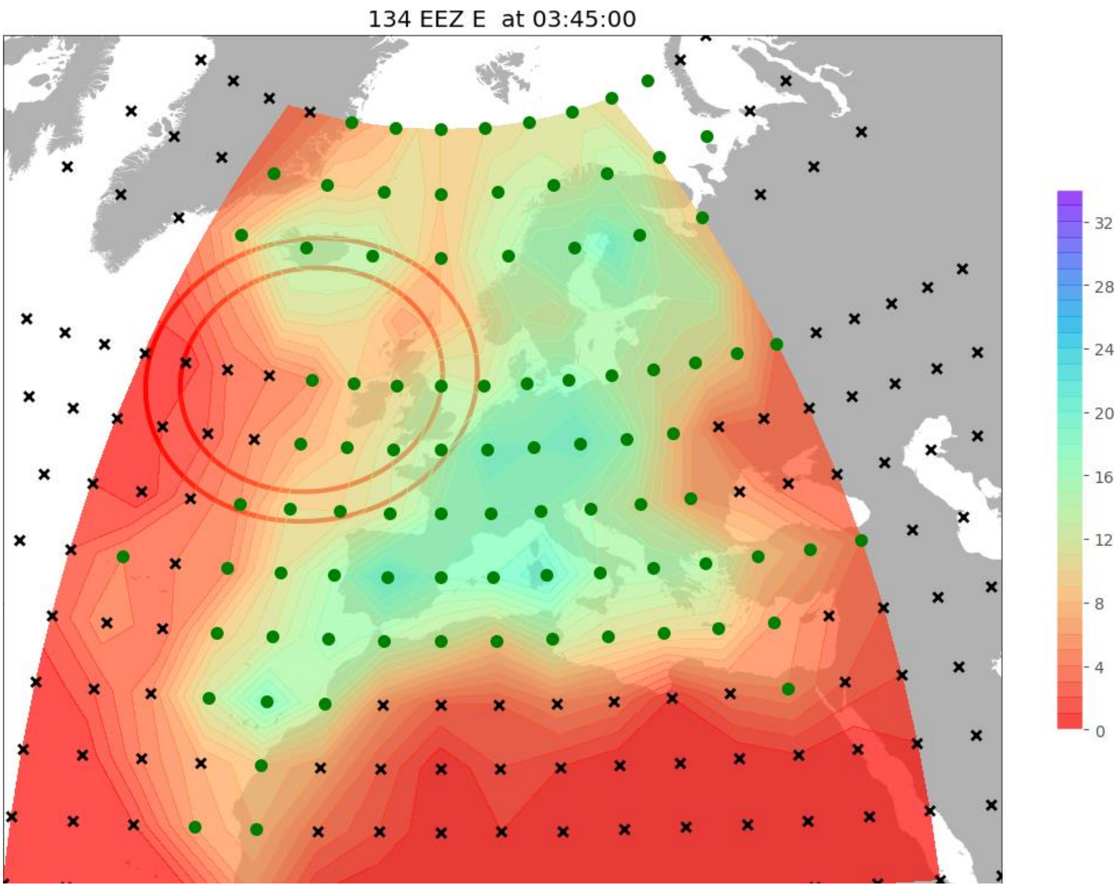


Figure 12: Ionosphere visibility from 55˚N, 15˚W.

It is clear that a significant proportion of the ionospheric grid, where pierce points from this user could pass, is not monitored. If satellites in that part of the grid are excluded, it is likely that the geometry of the remaining satellites will be significantly poorer. To illustrate this, we show a plot of the predicted 95% accuracy for a user at this location (Figure 13). Since we do not have real receiver measurement data for a user at this location, we show only the predicted 95% accuracy. The blue line shows the prediction based on a user elevation mask of 15˚ and demonstrates that there are numerous periods when the predicted 95% accuracy is worse than 10m. The likely explanation for this is the exclusion of satellites due to their pierce points being within a poorly monitored section of the ionospheric grid. To explore whether a lower elevation mask would improve the performance, we also show the predicted 95% accuracy with a mask angle of 10 ˚. It is clear that performance is improved, and that there is a reduction in the number of 'availability events', but there are still several spikes where the predicted performance is worse than 10m, and numerous occasions when the performance is in the 6-8m range.

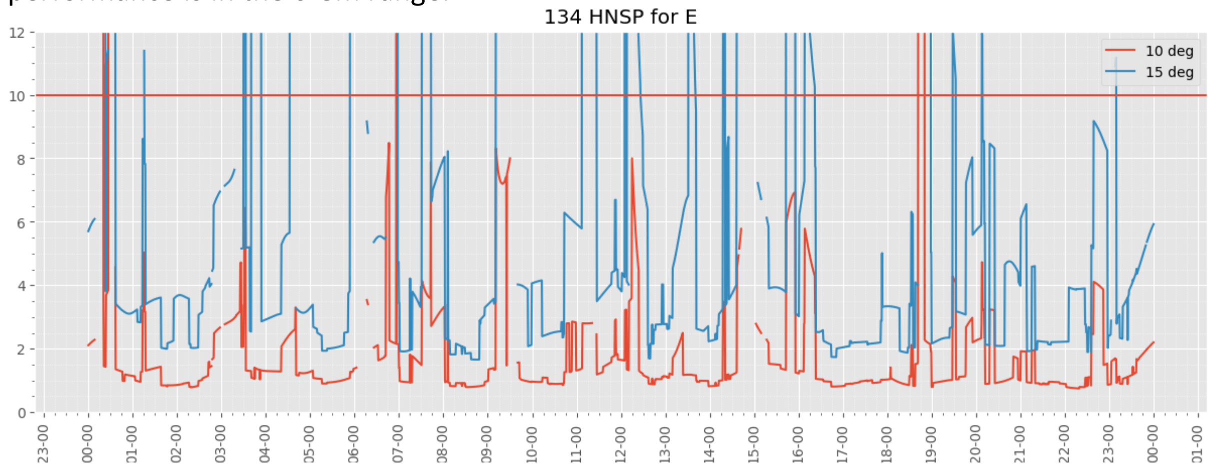


Figure 13: Predicted 95% accuracy for a user at 55˚N, 15˚W.

3.3 Further analysis - EGNOS Correction Weighting

The spike in EGNOS positioning performance discussed in section 3.1 was analysed further, for the observation at STOR at 15:00 on 14/05/19, depicted in Figure 14.

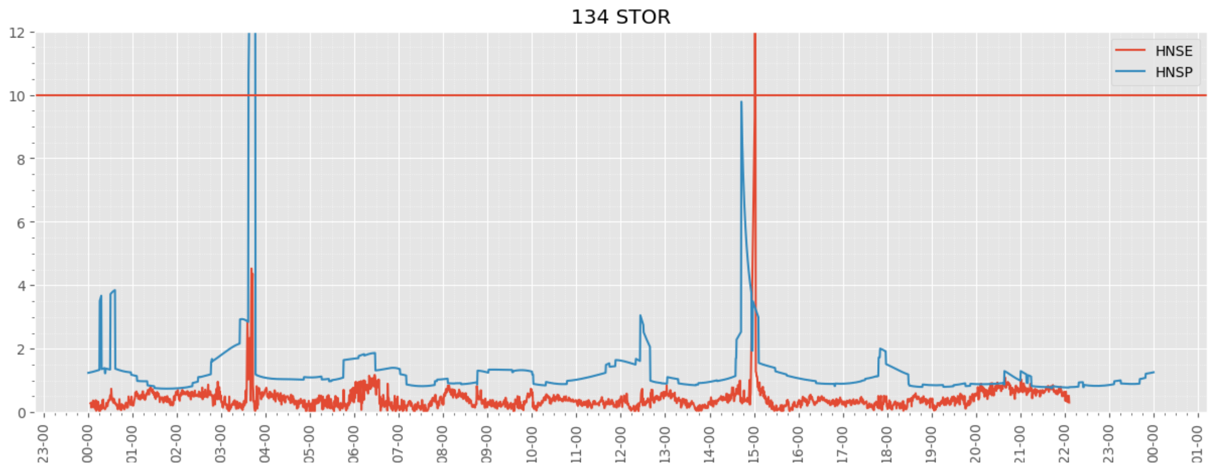


Figure 14: 95% accuracy plot for STOR on 14/05/19.

We first check whether the same spike is present in the uncorrected single point positioning (SPP) solution. Figure 15 below shows the EGNOS positioning results in more detail, while Figure 16 shows the equivalent single point positioning results. It is clear that the spike at 15:00 is not present in the SPP solution, which indicates that some feature of the EGNOS solution is responsible for the spike.

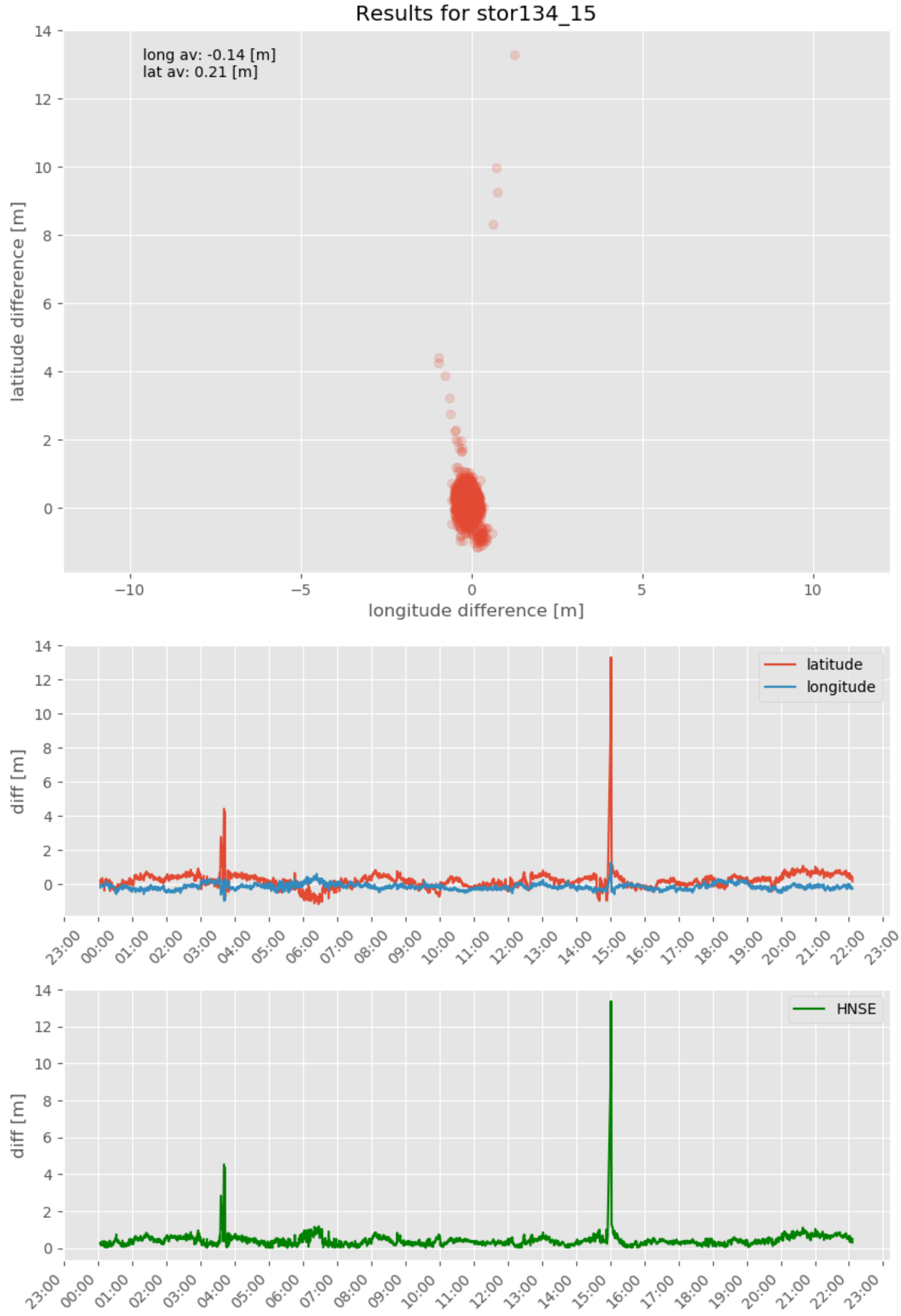


Figure 15 EGNOS Positioning Performance with 15˚ Elevation Mask

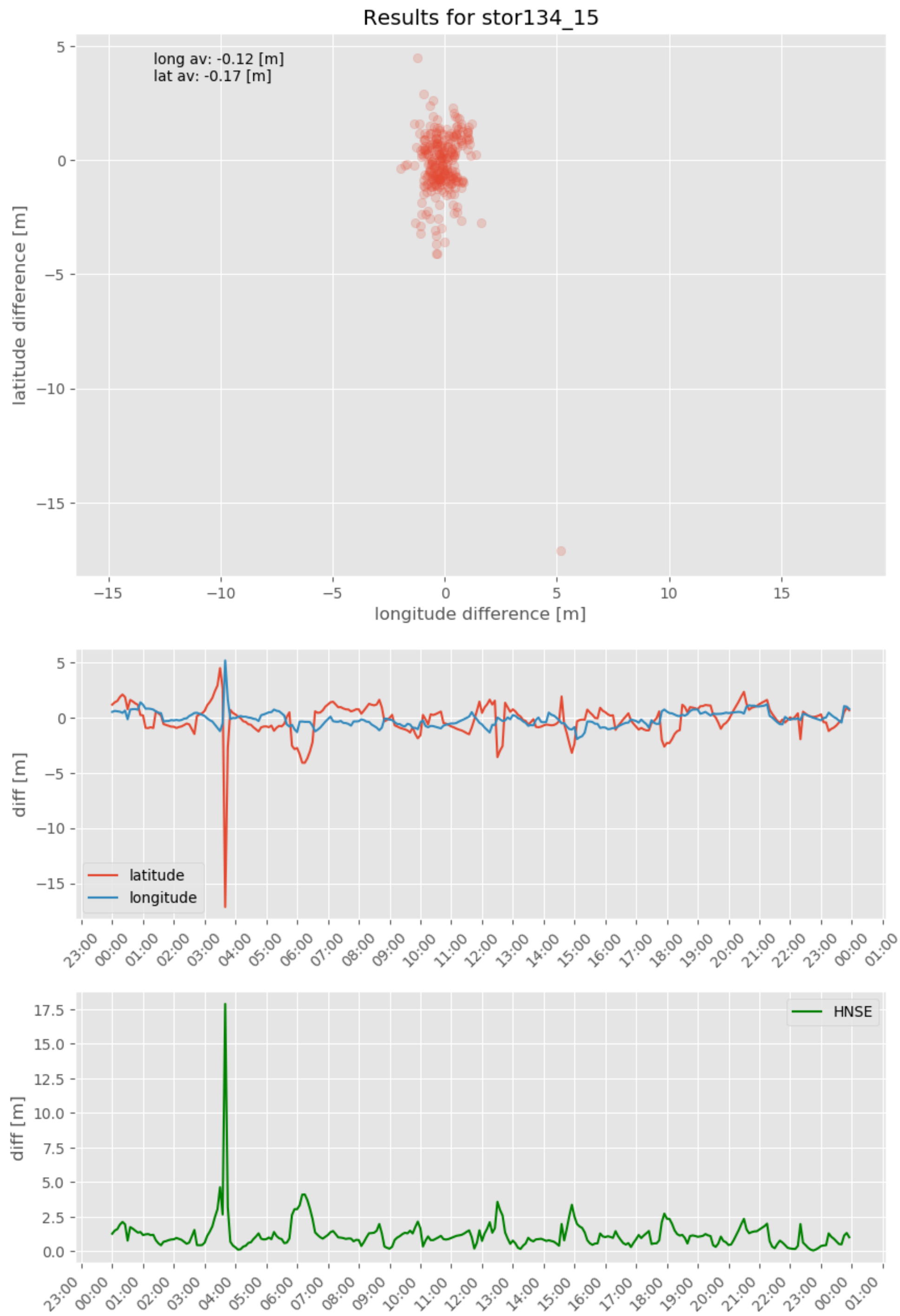


Figure 16: Single Point Positioning Performance with 15˚ Elevation Mask.

We next check whether the elevation mask angle has an impact on the spike. Figure 17 and Figure 18 show the EGNOS and SPP results for 10˚. It is apparent that the spike is considerably diminished in the EGNOS solutions, and remains absent in the SPP solutions. It should be noted that, contrary to the example under investigation here (15:00), other spikes are present in the SPP solutions, which are not present in the EGNOS solutions, indicating that the EGNOS corrections have successfully accounted for weaknesses in the SPP solutions, either by correcting measurement errors, excluding poor measurements, or giving them a low weight.

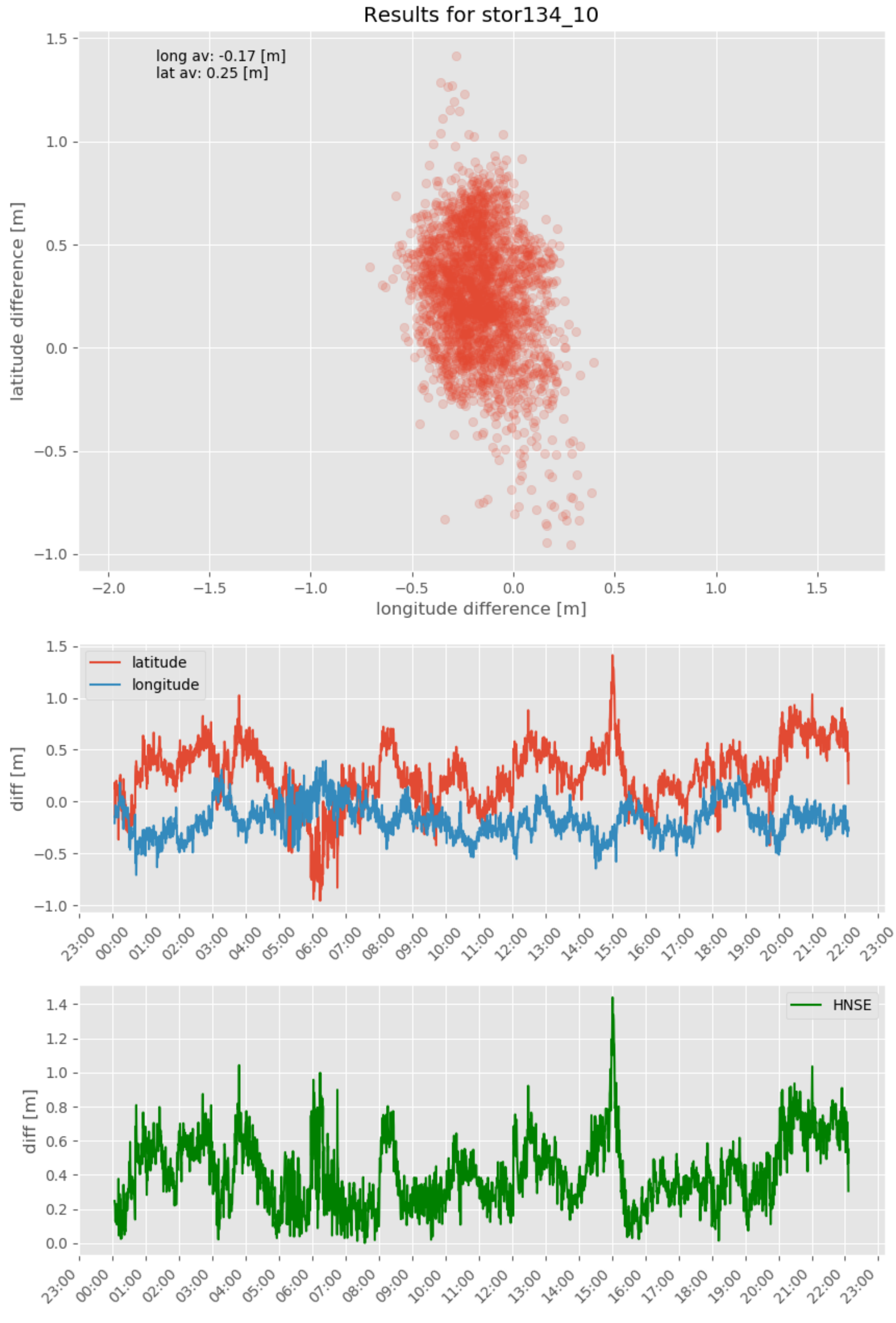


Figure 17: EGNOS Positioning Performance with 10˚ Elevation Mask.

The differences between the SPP and EGNOS solutions at the epoch under investigation suggest that the satellite geometry may be different between these two solutions, possibly due to the exclusion of one or more satellites by the EGNOS corrections. We next investigate the HDOP for the two types of solution, as output by gLAB. Figure 19 shows the EGNOS HDOP values for the three different elevation mask angles, and Figure 20 shows the same plot for the SPP solutions. It is clear that the EGNOS 15˚ solution exhibits a spike in HDOP at 15:00

which is not present in the SPP solution. The expectation therefore was that the EGNOS processing has excluded one or more satellites from the solution.

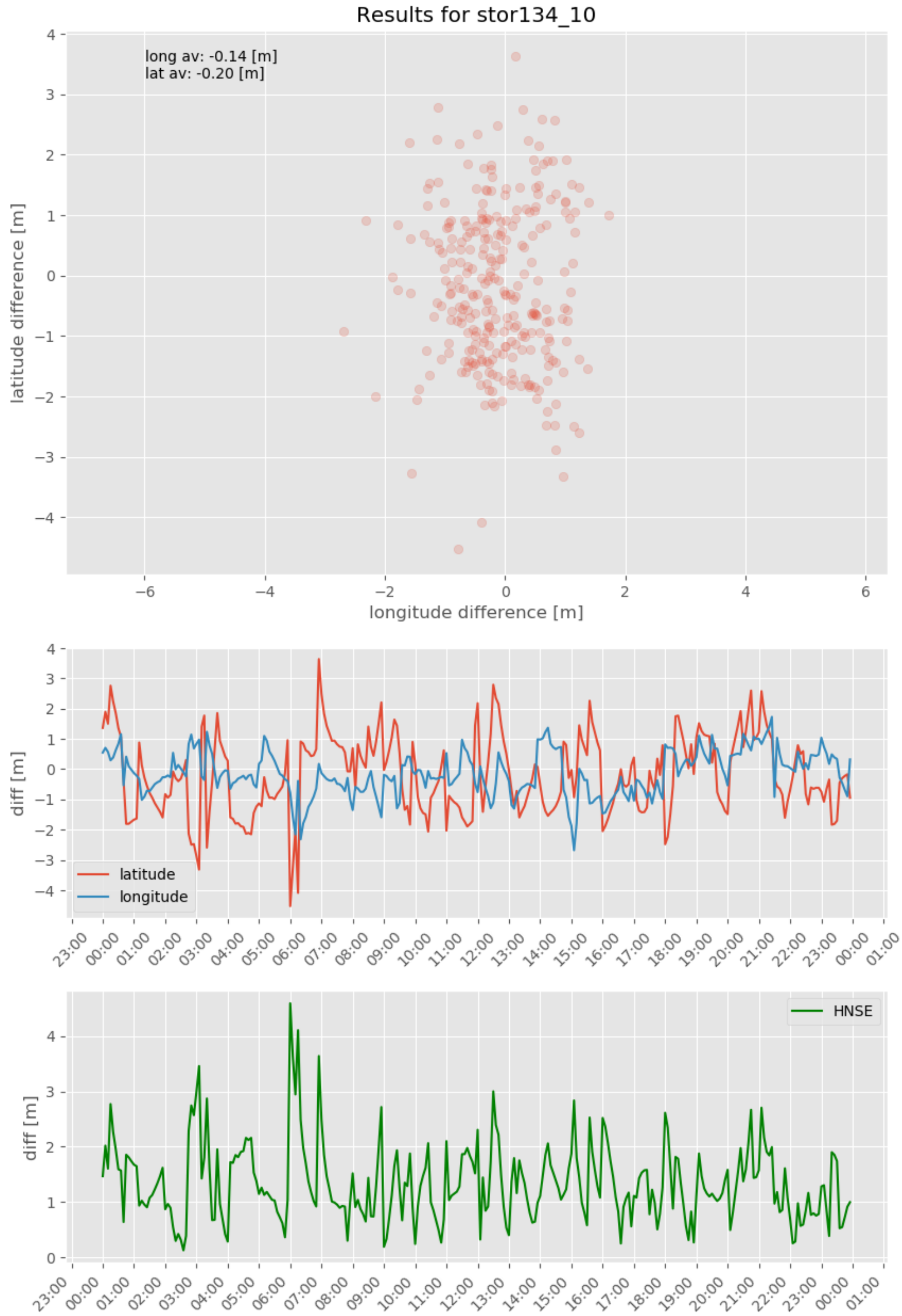


Figure 18: Single Point Positioning Performance with 10˚ Elevation Mask.

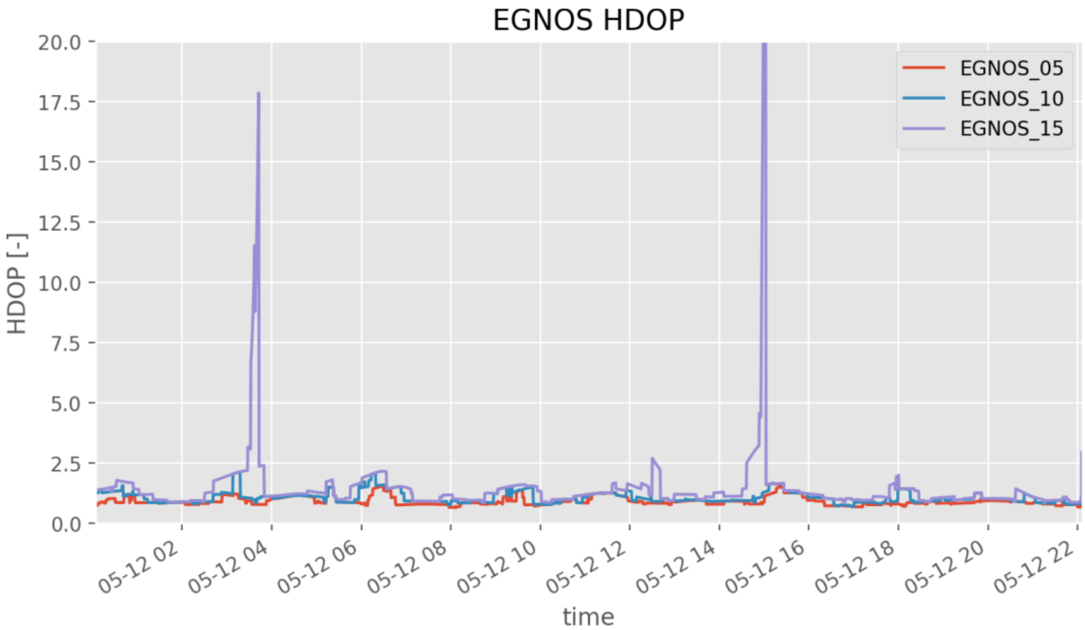


Figure 19: gLAB HDOP for EGNOS solutions at 5˚, 10˚ and 15˚.

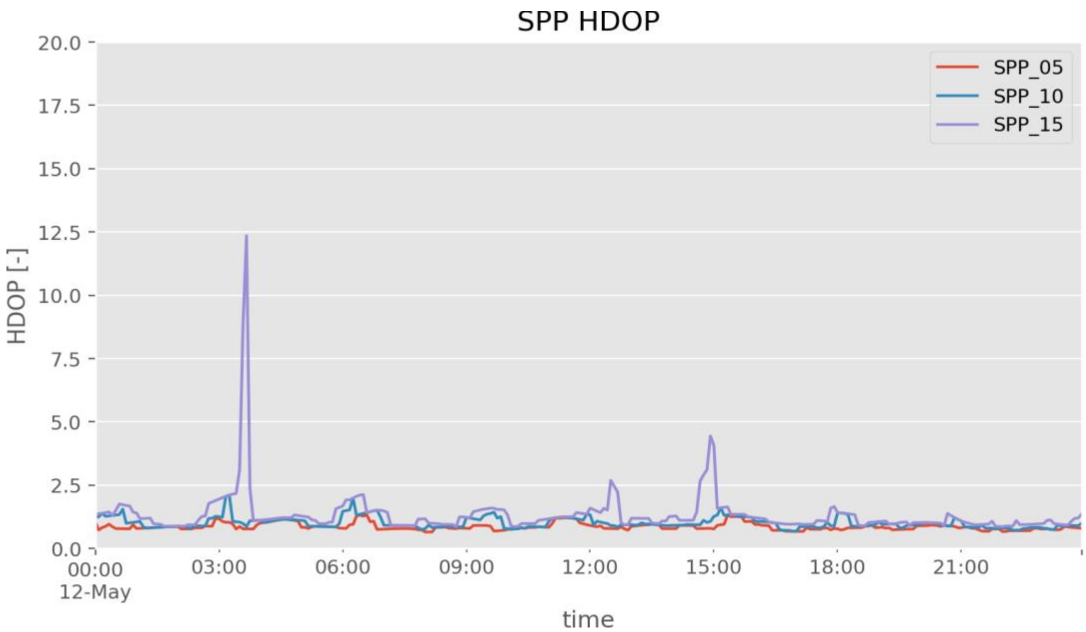


Figure 20: gLAB HDOP for Single Point Positioning solutions at 5˚, 10˚ and 15˚.

It is shown that the number of satellites used in the solution drops to 5 momentarily at 15:00 in both the EGNOS and SPP solutions. Since only the mask angle can be responsible for satellite exclusion in the SPP case, the implication is that the *same* 5 satellites are present in both solutions, and that they must have the same geometry. It is therefore concluded that the HDOP values output by gLAB must be *weighted* HDOP, i.e. the effect of measurement weighting must have been included. It is likely that gLAB uses an elevation dependent weighting function in the SPP solutions. In the EGNOS solutions, however, measurement weights will be obtained from the EMS (EGNOS Message Server) data files.

We can therefore conclude that the EMS messages at 15:00 have down-weighted one or more of the 5 satellites visible above the 15˚ elevation mask, resulting in poorer geometry, and it is this poorer geometry that is responsible for the spike in performance. Whilst the reason for the down-weighting is not explored here, it is clear from the equivalent SPP results that the measurement(s) in question do not contain abnormally high measurement errors, which implies that the down-weighting has arisen due to EGNOS modelling, e.g. insufficient tracking depth, or, more likely, increased IGP uncertainties.

With the lower elevation mask angles, the minimum number of satellites visible at 15:00 increases from 5 to 7 or 8, so the impact of the down-weighted measurement(s) among the subset of 5 is diminished. Nevertheless, although the performance spike is diminished with the lower elevation mask angles, it is still present, and in fact seems to be correlated to increased positioning error for approximately one hour before this event and 30 minutes after. The measurement down-weighting therefore appears to be related to a satellite that is present in the solution for an extended duration.

3.4 EGNOS v2 maritime conclusions for western EEZ coverage

The foregoing analysis has demonstrated that predicted EGNOS performance, using a calibrated simulation tool (SSv2), does not always meet the requirement for 10m (95%) accuracy. Spikes in performance contribute 'availability events'. With the resolution available from a deterministic simulation tool, e.g. 30 second samples over a 24-hour period, it is not useful, or meaningful, to attempt to quantify continuity based on these availability events.

However, an investigation of the causes of these spikes in performance has shown that the exclusion of some satellite measurements from a user's EGNOS position solution, due to the inability of the RIMS network to provide ionospheric corrections for those measurements, is their most likely cause. Exclusion of these satellites will result in worse DOP for the remaining satellites, which will probably result in a worse positioning solution. It will certainly result in a poorer 95% accuracy prediction. At locations further from the 'core' of the EGNOS RIMS network, the monitoring of the EGNOS ionospheric grid degrades, and it has been shown that the impact of satellite exclusion at the approximate western limit of the Irish EEZ is much greater than at coastal sites in the UK, with many more availability events being predicted.

These availability events can be mitigated by conventional beacon DGPS, where satellite exclusion due to a poorly monitored EGNOS ionospheric grid cannot be a factor – DGPS corrections for all common view satellites will be available, which will maintain full DOP, unless satellites are determined to be out of bounds. Historic data analysis has shown that DGPS can provide accuracy better than 10m during these predicted availability events.

They can also be mitigated by densifying the RIMS network in the area where the user receivers are affected by poorly monitored ionospheric grid points. The analysis has shown that the addition of just 3 extra RIMS at suitable north western locations could improve the monitoring of the ionospheric grid in the area where it affects users in the UK and Irish waters of their EEZs.

The findings presented in this report are based on a few test sites, and **it is not possible to make recommendations based on these limited results**. Nevertheless, they have highlighted an issue which could merit further investigation. Satellite exclusion due to inadequate ionospheric grid monitoring appears to lead to availability events, because the remaining satellites in the user's local constellation have reduced geometrical strength. Geometrical strength is very closely linked to the elevation mask employed by the user receiver. There is likely to be a trade-off between the improved geometrical strength that comes from a lower elevation mask angle and the greater atmospheric and multipath errors, leading to lower measurement weights, that will be present in low elevation measurements. It is suggested that this should be studied in more detail. In addition, an investigation of the correlation between historic EGNOS corrections, from EMS files, and the SSv2 model predictions, should be undertaken, to corroborate the examples where predicted 95% position error exceeded the 10m threshold.

It is clear that the elevation mask angle applied to the EGNOS positioning solutions has a significant effect on the performance. The trade-off between improved satellite geometry and increased measurement errors, arising from variations in the user receiver elevation mask, should be investigated, to determine whether the exclusion of satellites due to ionospheric monitoring can be mitigated by the inclusion of measurements with slightly higher measurement errors. This should help to inform the choice of a standardised user receiver elevation mask.

4 Maritime EGNOS v3 and M-RAIM

4.1 Complementary use of EGNOS v3 and M-RAIM

The study has provided a detailed explanation of issues and potential solutions concerning the use of Satellite Based Augmentation Systems (SBAS) and Receiver Autonomous Integrity Monitoring (RAIM) in the provision of user-level integrity and continuity for GNSS-based positioning in the future maritime environment. Those solutions are aimed at the 2025 timescale and beyond, for implementation in a vessel’s future Multi-Constellation Multi System Receiver (MSR). As such, the contents of this section look beyond the introduction of the ‘EGNOS V2 A.1046 maritime service’, expected in early 2022, and which provides integrity at system-level only. The user-level integrity solutions envisage a possible future maritime SBAS service that may derive from EGNOS Version 3 (V3) or an alternative SBAS, covering both GPS and Galileo and dual frequency (L1/L5 and E1/E5a) operation.

The proposed solutions draw upon mathematical analyses of two autonomous integrity approaches: Isotropy Based Protection Level (IBPL) and Maritime RAIM (M-RAIM). The derivation of M-RAIM (as an adaptation of aviation Advanced RAIM to maritime) forms part of the GLA’s (Trinity House’s) background IP declared under the NAVISP Element 3 contract with ESA for the MarRINav project. M-RAIM is considered herein to be the principal effective approach to user-level integrity of maritime navigation and it is included in full detail in the MarRINav D3b report with the intention to promote its development, making it freely available to marine receiver manufacturers and other stakeholders without licence constraints or royalties.

The contents of technical analysis, discussion and mathematical derivations in this study have been peer reviewed in detail by experts from Stanford University in the US. This was separately funded by the General Lighthouse Authorities of the UK and Ireland (GLA) as part of a separate review of the background IP for M-RAIM, who acknowledge the substantial value of the Stanford review as a significant contribution to the future safety of maritime navigation.

In Europe, the EC is planning a maritime service based on the existing evolution of EGNOS, known as Version 2 (EGNOS V2). This could possibly be introduced as early as 2022. The proposed service would provide warnings to mariners of GPS system faults. It would protect the vessel against errors in position caused by malfunction of GPS satellites or ground processing. This capability is termed “position integrity at system level”. Vessels regulated by IMO Safety of Life (SOLAS) resolutions would need to be equipped with new type-approved receivers to benefit from this service.

However, simply delivering “integrity at system level”, through EGNOS V2 (or the marine beacon DGPS system), fails to take into account position errors caused by disturbances to the navigation satellite signals local to the vessel. This raises the fundamental question of whether current aviation designs are suitable for maritime service. Perhaps surprisingly, the accuracy and continuity requirements for maritime port and harbour approach are higher than those for aircraft approaches that can be supported by satellite navigation. In addition, there are, as yet, no extensive databases of satellite signals received on ships, equivalent to those in aviation. Indeed, observations show that maritime receivers experience more satellite signal blocking and reflections (multi-path), and more radio interference than do those on aircraft. There are also recent reports of possible spoofing of ships receivers. So, while the use of SBAS assures the reliability of the navigation signals transmitted from space, its ability to guarantee the quality of signals received on a ship is limited.

Recent studies, such as the SEASOLAS project of the European Global Navigation Satellite Systems Agency (GSA), have made good progress in establishing operational requirements for a maritime SBAS service. They have identified technical approaches to the maritime use of the next version of EGNOS, V3. These include emerging options for candidate receiver algorithms that estimate position errors and raise alarms when the errors threaten safety of navigation or the success of operations. We term this capability: “integrity at user level”. As yet, no method has been shown to meet both the integrity and continuity standards required to ensure safety of life at sea, on the evidence of satellite signals received aboard ships.

The EGNOS V3 designed for aviation is not optimised to provide the information needed to satisfy user level requirements. EGNOS error overbounds are assessed very conservatively for aviation and applications, whereas maritime integrity may be better accomplished using best-estimate “fault free” error models (and associated fault probabilities) rather than the inflated aviation overbounds. It is necessary to determine a nominal vessel multi-path model, and the associated probability that instantaneous measurements exceed this model (fault probability). This issue could be addressed by changing the system requirements for data parameters provided by EGNOS (and other SBAS around the world), or even by considering a new and separate maritime specific SBAS message. This may involve the integrity bound being broadcast as pairs of mean and standard deviation parameters for each satellite. Potentially, the ideal solution could be for aviation, maritime and other applications each to have its own optimised receiver design to use the SBAS information in the most appropriate way.

Those developing EGNOS V3 and its complementary receiver software will wish to ensure that not only the signals transmitted from space but also those received on ships meet the high maritime integrity and continuity standards. Success in achieving this will require receivers that can cope with the signal errors caused by multi-path and interference. The SEASOLAS project identified two potential solutions to this: IBPL and M-RAIM.

IBPL (Isotropy-Based Protection Level) is a proprietary algorithm developed by the Spanish technology group GMV. It has been designed to allow GNSS receivers to establish their integrity autonomously, especially in urban environments. The technical analysis of IBPL presented in this study, based on the rigorous mathematics described in detail, assessed the capability of IBPL against the maritime performance requirement for continuity. It considers the imbalance between integrity and continuity that would arise from use of IBPL on ships. It is also noted that the “isotropy” assumption on which IBPL is based is fundamentally untrue in the maritime environment and that IBPL should not be implemented in marine receivers for general maritime navigation.

M-RAIM is an adaptation for maritime conditions of the principal RAIM algorithm now under development for deployment in airborne receivers: Advanced RAIM (ARAIM). M-RAIM was developed by the GLA as an adaptation of ARAIM for maritime. The technical analysis of M-RAIM, based on the detailed mathematics presented in this study, considered the capability of M-RAIM to satisfy both maritime integrity and continuity performance requirements. In particular, the capability of M-RAIM to handle multiple simultaneous GNSS signal faults has been investigated. M-RAIM could work as complementary to and in conjunction with SBAS or be used standalone (especially in locations outside SBAS service coverage).

4.2 Conclusions and Recommendations

1. It would be more difficult and costly to utilise IALA Beacon DGPS than EGNOS V3 (or alternative SBAS) for the future provision of maritime navigation integrity at user-level.

   Recommendation: The dual frequency multi constellation (DFMC) capability of EGNOS V3 (or alternative SBAS), supported by the ship's Multi System Receiver (MSR), should be used in the development of position integrity for vessels rather than modifying the beacon system.

2. SBAS (EGNOS V3) alone will be insufficient to address user-level integrity for general maritime navigation due to the local GNSS signal reception environment (noise, interference, multi-path and non-line-of-sight reception) on vessels.

   Recommendation: Receiver algorithms for receiver autonomous integrity monitoring (RAIM) should be designed, and an appropriate IEC test specification produced to ensure future type approved receivers adequately protect the user from potentially misleading GNSS errors caused by effects local to the vessel.

3. Maritime RAIM (M-RAIM) is a method that shows considerable promise as a candidate form of RAIM for inclusion in the maritime user-level integrity solution.

   Recommendation: M-RAIM should be researched further and evaluated for implementation in future maritime receivers when used either in combination with SBAS (e.g. EGNOS V3) or standalone (for locations outside SBAS coverage).

4. The fundamental assumption of IBPL autonomous receiver monitoring is not generally valid in maritime operations and IBPL cannot be relied upon to provide user-level integrity and continuity on vessels.

   Recommendation: IBPL should not be implemented in receivers for general maritime navigation.

5. Existing SBAS (EGNOS V3) information planned to be provided for aviation is not ideal for determining maritime user-level integrity and hence provision of the underlying SBAS error statistics[1] would assist solutions for user-level integrity.

   Recommendation: Changes to EGNOS parameters or transmission of an additional maritime message should be investigated to evaluate whether the provision of maritime specific information would be cost-effective.

6. It is recognised that the capability for future SBAS integrity bounds to be broadcast as separate mean and standard deviation figures, allowing the broadcast error to more closely match the expected fault-free error without excessive inflation, may not be cost-effective.

   Recommendation: The feasibility of making changes to the broadcast SBAS information should be investigated further; also the idea suggested by Stanford to develop a table that allows the determination of fault free sigmas, nominal biases, and faulted biases from already broadcast error bound information.

7. Protection levels derived from SBAS and RAIM may be overly conservative if they are driven by "worst-case" fault scenarios and a "specific risk" integrity design.

   Recommendation: Consideration should be given to "specific" vs. "average" risk; a "fault-averaged risk" approach would provide some degree of probabilistic averaging over the prior probabilities of faults. It is noted that M-RAIM adopts a "fault-averaged risk" approach based on a-priori fault probabilities.

8. The use of dual frequency combinations in maritime may lead to an inflation of error bounds due to a multiplication factor on multipath imposed by the iono-free measurement combination. However, single frequency L5/E5a is potentially a poor choice because the ionospheric delay is 1.8 times larger than L1/E1, and more importantly so is the uncertainty (GIVE and corresponding UIRE would need to be multiplied by this number).

   Recommendation: The advantages of dual-frequency L1/L5 (E1/E5a) use against the use of single-frequency L1/E1 or L5/E5a for maritime positioning should be investigated further by trade-off analysis.

[1] Ideally a bespoke SBAS maritime service message would broadcast fault-free estimates of UDRE and GIVE, recognising this may not be a cost-effective option. Other options that could be considered are (i) a single bespoke data-field within another SBAS message defines a maritime scale-factor (e.g. x2.5) by which to reduce the aviation UDRE and GIVE bounds to yield effective maritime fault-free estimates of these parameters, and (ii) a bespoke table is implemented to convert broadcast UDRE and GIVE index parameters to appropriate fault-free error estimates, employed exclusively by maritime receivers

9. For M-RAIM, it is necessary to determine a nominal vessel multi-path model, and the associated probability with which instantaneous measurements exceed this model (fault probability).

   Recommendation: More information should be gathered from real-world measurements in the maritime environment (including how the environment varies under different operational conditions) to establish a multi-path model, and the associated probability with which instantaneous measurements exceed this model (fault probability).

10. PPP is a powerful technique to combat multi-path, but user-level integrity for PPP has not yet been developed.

    Recommendation: PPP for maritime applications should be researched further but PPP should not be used for general maritime navigation until and unless a user-level integrity solution has been developed.

4.3 Way Forward

A collaborative way forward is required for MarRINav Stage 2, working closely with the EGNOS experts in ESA. The way forward is depicted in Figure 21.

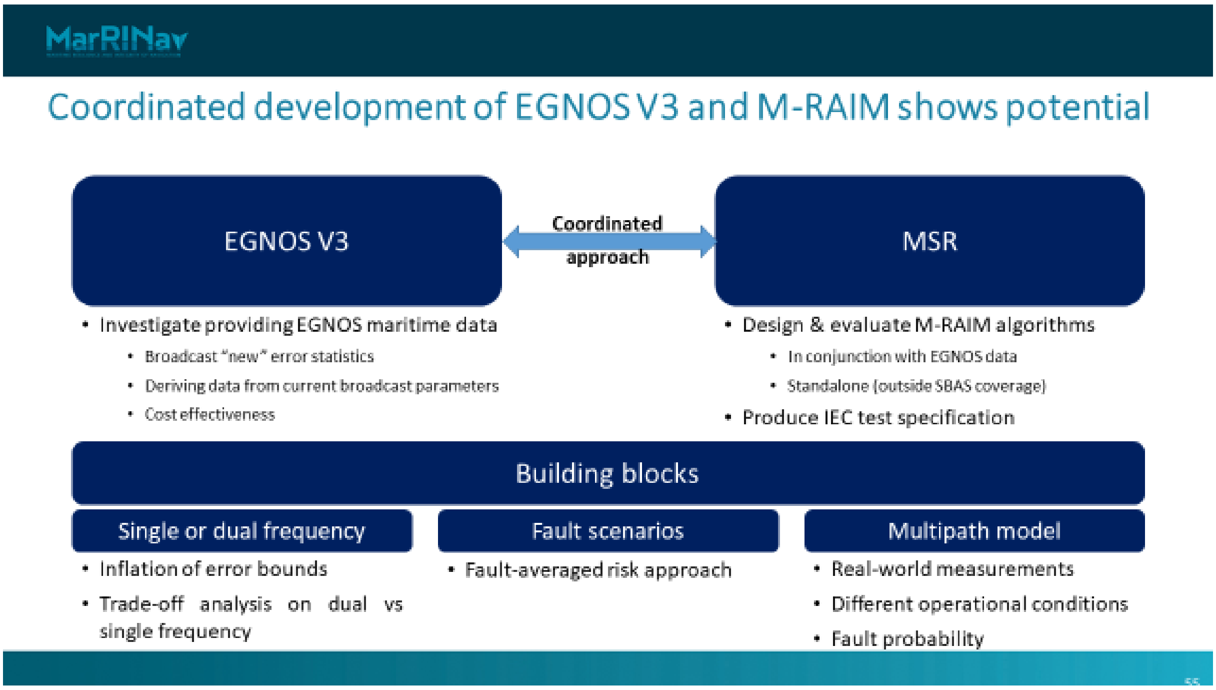


Figure 21: Way Forward as a Coordinated Development

5 Resilient PNT Technology Options

5.1 Overview of technology options

A range of options for R&I (Resilience and Integrity) PNT had been analysed in previous studies. Candidates include wide-area systems such as eLoran and the Satelles' System Timing and Location (STL), regional area systems such as MF R-Mode and VDES R-Mode and local-area systems with local infrastructure such as LOCATA at ports. Options include the use of ships' radars with coastal Enhanced Radar Beacons ('eRacons') with positioning through a process referred to as "radar absolute positioning". In addition, the technology candidates include ship-based systems such as dead reckoning based on speed log and gyro compass and electronic visual aids such as the ePelorus. Since future maritime Critical National Infrastructure (CNI) will need to provide coverage of the whole of the UK Exclusive Economic Zone (EEZ), which includes complex sea spaces such as the North Sea, it is likely to require a system-of-systems solution with contributions from the above dissimilar complementary sources.

The core or primary, PNT system is assumed to be multi-constellation, multi-frequency GNSS, implemented in the IMO's Multi-Constellation Multi-system Receiver (MSR). The MSR will have access to at least three GNSS, including GPS and Galileo. The considerations of resilience includes methods of GNSS hardening, including through the use of active antenna systems, multiple antenna systems, plausibility tests and jamming and spoofing detection devices. The key questions addressed by this part of the MarRINav project are: 'What candidate Resilient PNT systems can be deployed to meet users' requirements?' and 'How do we integrate multiple systems?'

The objective is to identify key maritime Resilient PNT and communications systems to the Resilience & Integrity of the maritime Critical National Infrastructure of the United Kingdom, but with a view to the wider **cross sector** implications and capabilities. A fundamental principle of this work is the realisation that, for the UK only, it is likely that a single source of Resilient Position Navigation and Timing will not be sufficient to provide the required coverage performance in terms of accuracy, integrity, continuity and availability. The approach is to investigate the development of a hybrid system-of-systems, recommended to include:

- eLoran
- VDES R-Mode
- Radar Absolute Positioning
- Satelles (STL), subject to confirmation of performance
- LOCATA
- Onboard systems, to integrate traditional and/or inertial Dead Reckoning.

5.2 eLoran

Enhanced Loran (eLoran) is a low-frequency, long range Terrestrial Radionavigation System, capable of providing positioning, navigation and timing (PNT) service for use by many modes of transport, including maritime. eLoran transmits pulsed groundwave signals with a central frequency of 100kHz. This low frequency gives the signals their **LO**ng **RA**nge **N**avigation capability from widely spaced transmitters. The receiver's position is determined by the measurement of the times of arrival (TOA) (or pseudorange) of these pulses. Pseudoranges from at least three transmitters are required to be measured in order to determine a horizontal position solution by trilateration. Since the transmitters are placed on the Earth's surface, altitude of the receiver cannot be determined. Measuring more than three transmissions (preferably five) provides the user with RAIM (Receiver Autonomous Integrity Monitoring) capability in addition to positioning accuracy. A precise clock aboard the vessel, and providing precise time to the onboard eLoran receiver, would allow the use of one less transmitter.

An eLoran transmitter broadcasts a group of 8 'navigation' pulses, transmitted at 1 millisecond spacing. However 9th and 10th pulses may be added in order to implement the Loran Data Channel. All eLoran transmitters transmit at the same frequency, so they cannot all transmit at the same time. Instead one transmitter, designated the Master, transmits a group of pulses followed a set time later by one of several successive Secondary transmitters. The time delay between the Master transmission and a Secondary is called the Emission Delay (ED) of that Secondary. The time interval between successive Master station transmissions within the same group is called the Group Repetition Interval (GRI), also sometimes referred to as the "rate". A Secondary transmitter's Emission Delay includes the signal propagation delay between the Master and the given Secondary, and a Coding Delay intended to position the Secondary transmissions within the GRI such that nowhere in the coverage area do the transmissions overlap.

5.2.1 Maritime eLoran

A maritime eLoran system includes the following elements:

- Several eLoran transmitters broadcasting a UTC synchronised and standardised eLoran signal.
- The signal incorporates a data message channel (the Loran Data Channel), which may take several forms.
- An identified service area, in which the signal propagation characteristic, represented by Additional Secondary Factor (ASF) data, has been measured or modelled through software with the resulting modelled data calibrated using a much smaller set of measurements than would otherwise be required without such modelling.
- Where accuracy is required to support the Port Approach Voyage Phase, differential-Loran (DLoran) Reference Stations shall be installed. These reference stations calculate differential corrections, which are sent to eLoran transmitters via an Internet Virtual Private Network (VPN) for broadcast to the mariner via the Loran Data Channel for reception using the same eLoran receiver used for positioning.
- An infrastructure based integrity monitoring system (system integrity) that takes two main forms:
    - Alarms and alerts concerning the health and status of eLoran transmitters and their associated transmissions and the health and status of DLoran reference stations and their transmitted differential-corrections;

  - The capability to monitor the effects of solar weather is required in locations that are particularly prone to such effects (geomagnetic storms, proton events, coronal mass ejections, etc.). Integrity monitors of this kind remotely monitor the quality of the received signals and are able to interface to the Loran Data Channel in order to issue timely system-level integrity warnings.
- A Control and Monitoring Centre, which provides a remote human/machine interface to the set of transmitters and/or DLoran reference stations.
- A data communications backbone (the Operational Data Network) is required for the various components of the system to communicate with their respective Control Centres.
- An eLoran receiver aboard ship will be integrated within the MSR.
- The receiver will possess a RAIM algorithm for user-level integrity monitoring, where a sufficient number of transmitters are available.
- ASF data, and transmitter and reference station almanacs will be disseminated by e-Navigation services.

The above system should provide better than 10 m (95%) position accuracy for port approach phases of the voyage. Figure 22 illustrates an overview of the eLoran system for maritime port approach.

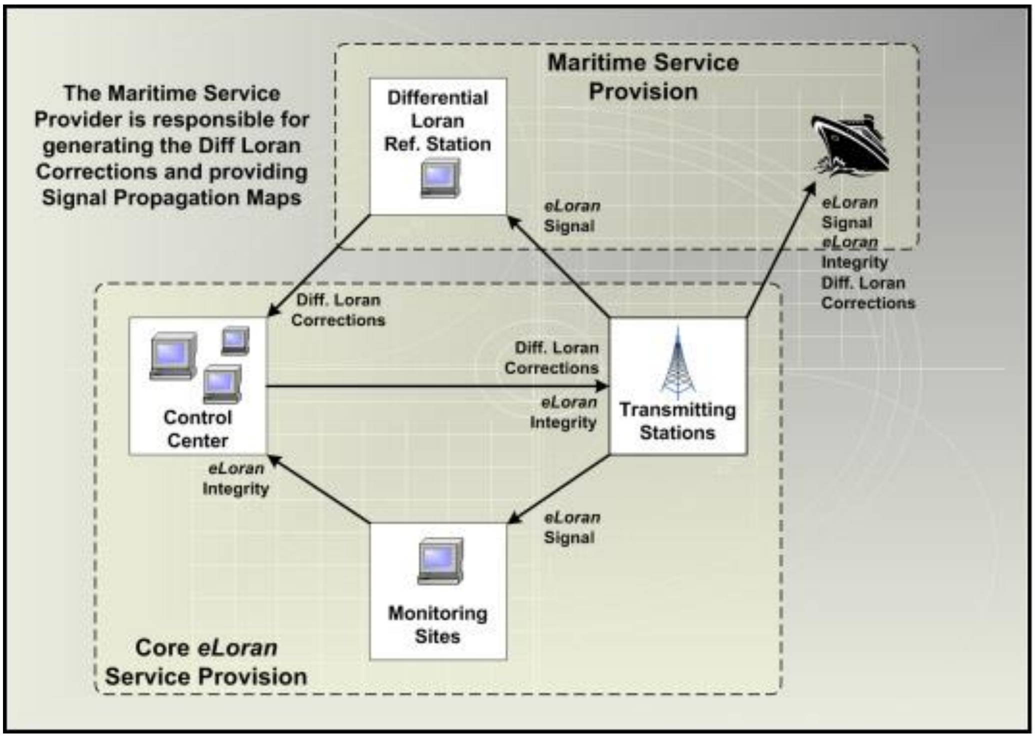


Figure 22: The service architecture for eLoran and the components required. Source: *'eLoran Definition Document', V1.0, October 2007, International Loran Association* [10].

In Coastal Voyage Phase, eLoran may be used without differential-Loran because the distances to the nearest reference stations will be too great for the differential corrections to be valid. During this voyage phase the mariner will rely, in the first instance, on the use of accurately *modelled* ASF data that has been produced by computer simulation of eLoran propagation and then 'factory' processed and calibrated using a sparse set of ASF *measurements* taken in an efficient manner over a wide area. The resulting modelled, but calibrated, ASF data shall be again stored within the users' receivers.

Modern eLoran receivers operate in all-in-view mode – this works just like GPS. In all-in-view, if we were to look at all points on the Earth where we measure the same propagation time from a transmitter and plotted those points on a navigation chart, we would see that all those points lie on a circle with the transmitter at the centre. Taking measurements from three such transmitters, thus forming three circles, allows a receiver to compute its position. In order to measure the propagation time each transmission needs to be synchronized to a precise clock, common to all transmitters.

5.3 VDES R-Mode

Ranging mode (R-Mode) refers to the addition of a ranging capability to existing or new marine data transmissions. Ranging systems work by measuring the time of flight, or time of arrival, of radio signals to estimate the distance between the user and multiple known base stations. If sufficient stations are available, the user's position can be calculated by multilateration. As a side product, the user's clock offset with respect to the system clock is also determined. Measurements from different ranging systems can be combined to form a single resilient Position, Velocity and Time (PVT) solution, as envisaged in IMO Resolution MSC.401(95) on the Performance Standards for Multi-system Shipborne Radionavigation Receivers (MSR) and the associated Guidelines for Shipborne PNT data processing, MSC.1/Circ.1575 [8].

Two concepts for R-Mode are currently being studied by the international maritime community, based on the medium-frequency signals of the IALA Marine Beacon DGPS system of base station networks of the Automatic Identification System (AIS) and its planned successor, the VHF Data Exchange System (VDES). The focus of this section is on the AIS/VDES variant of R-Mode [11], [12].

R-Mode Baltic is an ongoing European Union-funded project, which aims to set up an R-Mode testbed in the Baltic Sea by 2020 [13]. The project considers both Marine Beacon DGPS and AIS R-Mode, with a view to investigating the possibility of also using VDES for ranging. R-Mode Baltic has so far considered eight options for implementing AIS/VDES R-Mode, as summarized below and trials of these techniques are currently being prepared:

1. Use of a single AIS channel, the standard AIS GMSK modulation and a data sequence optimized for ranging precision; the use of Gold codes is being considered in order to enable the simultaneous use of one AIS channel by multiple base stations.
2. Use of a single AIS channel in conjunction with two additional continuous wave ranging signals.
3. Simultaneous use of two AIS channels, the GMSK modulation and an optimized data sequence.

4. Simultaneous use of two AIS channels in conjunction with two additional continuous wave ranging signals in each channel.
5. The same waveforms as in 3 or 4 above but using the two AIS channels sequentially.
6. Any of the options 1 to 5 above in conjunction with the use of additional VDES channels.
7. Use of standard (random) data VDES transmissions.
8. Use of VDES transmissions in conjunction with an alternating symbol pattern designed to enhance the ranging performance.

The possibility of using active (two-way) ranging in AIS/VDES R-Mode, as opposed to passive pseudoranging, has also been studied. In most coastal areas, positioning accuracy using pseudoranging will be significantly degraded due to poor solution geometry as most (if not all) usable base stations will be located to one side of the vessel (unless additional base stations are deployed on offshore platforms). In active ranging, measurements are carried out in both directions between a ship and the base station. The measurements have equal-size and opposite timing biases, so the range can be obtained by taking their average. Consequently, no synchronization of the base station clocks is required and a position may be determined using one fewer station than required by pseudoranging. Additionally, for pseudoranging, the base stations must surround the user to obtain good geometry, whereas for two-way ranging, they need only subtend 90°.

However, active ranging would lead to an unacceptable increase in the AIS/VDES data link loading and would mean that only a limited number of ships could use the system simultaneously. IMO Resolution A.1046(27) states that 'systems should be capable of being used by an unlimited number of ships' and this **may** rule out active ranging. However, the availability of two-way ranging functionality cannot be discounted, particularly if it is possible to derive knowledge about the loading of the VDES data channel at the time the ranging functionality is required.

For pseudorange-based positioning, the shipborne receiver will need to observe signals from at least four R-Mode-enabled stations, sufficiently distributed in azimuth around the location of the ship. Five signals would be required for RAIM-based integrity. The required number of stations can be reduced by one if the geometric ambiguity is resolved using prior information. It can further be reduced by one if the shipborne clock offset is eliminated (either by using active ranging, or through a combination of active and passive ranging and high-stability on-board clock).

There currently is not a single agreed approach to AIS/VDES R-Mode. It is likely that several system design iterations will need to be developed and trialled in order to verify the feasibility of the concept and identify the optimal approach. However, for the purpose of the MarRINav project it is assumed that first generation VDES R-Mode systems will:

- Operate by measuring the time of arrival of VDES (noting that VDES includes AIS) transmissions accurately synchronized to a common time base;
- Use standard VDES waveforms and channel bandwidths;

- Use either ordinary (random) data transmissions or dedicated R-Mode data sequences optimized for ranging precision;
- Not require real-time propagation corrections.

VDES R-Mode could be considered for installation at existing UK and Irish AIS stations shown in
Figure **23**.

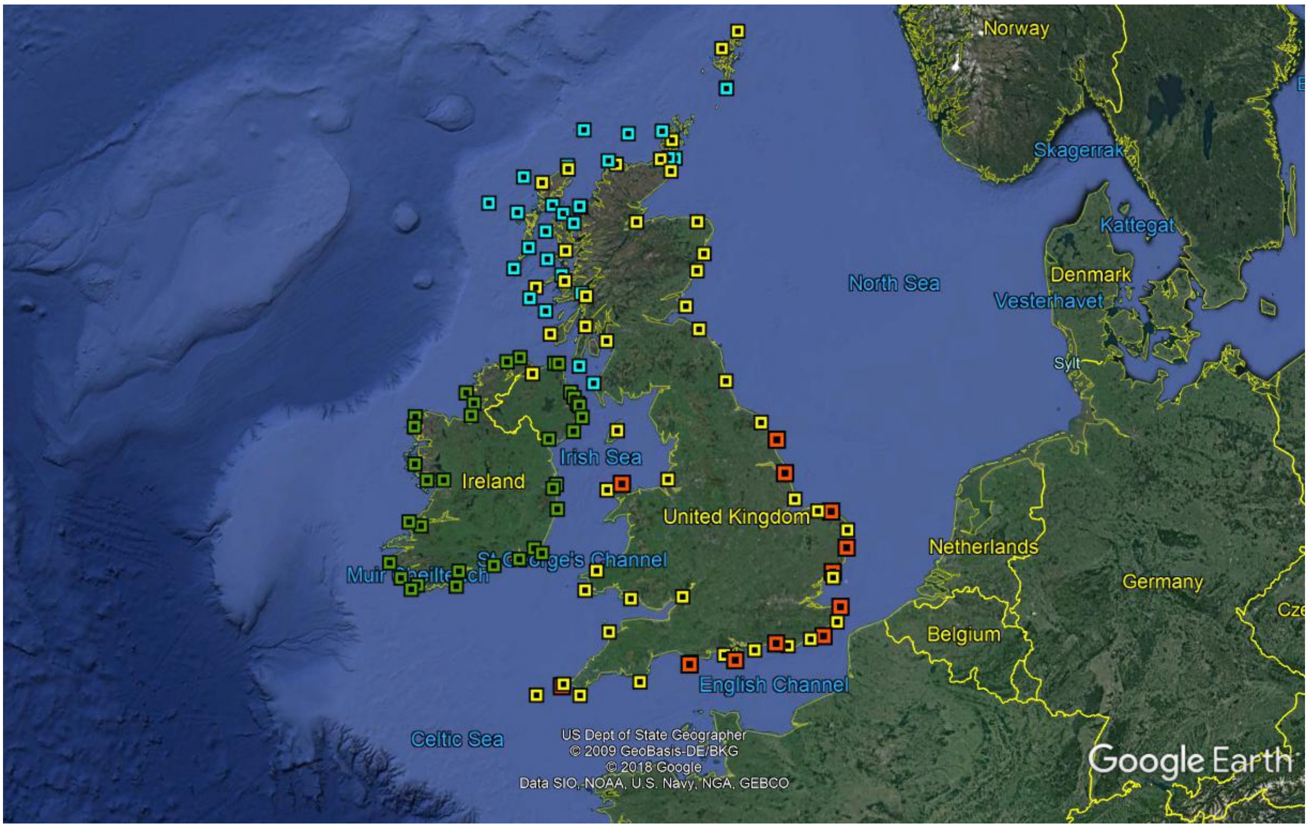


Figure 23: Map of UK and Irish AIS base stations

5.4 Radar Absolute Positioning

A Radar system emits short chirps of high-intensity GHz-frequency radio energy, via a transmitting antenna. The pulses propagate through the atmosphere until they encounter a radio-reflective target. Upon striking the target the pulse is scattered and a certain amount of the radio-frequency energy is directed back towards the radar antenna. A marine radar is monostatic. By measuring the elapsed time between emission and reception of a pulse, and knowledge of the speed of light, the range to the radar-reflective object can be determined. The radar emits pulses in an azimuthally narrow "beam"; reception of a pulse thus provides both range and bearing information. Typically, marine radar systems operate a rotating radar antenna, which continually radiates radar pulses. Comparing the time of the radar returns with the angle of rotation of the antenna provides relative-bearing information to the vessel.

Combining radar bearing information with knowledge of the vessel's heading (via magnetic compass or ship's gyrocompass) enables the absolute-bearing of each radar return to be calculated and a 'North-Up' display can be provided. The accuracy of a North-Up display is dependent on the accuracy of the vessel's heading-measurement relative to True North.

The SOLAS convention [14] requires that all marine vessels of 300 gross tonnes and upwards (and all passenger vessels) be equipped with one radar operating in the X-band (9 GHz, or 3 cm wave-length). All vessels of 3000 tonnes and upwards shall also equip one S-band (3GHz, or 9 cm wave-length) radar. There is little practical difference between X and S-band radar: both are operated in much the same way, and both are GHz-frequency (cm wavelength) so operate only along a direct line-of-sight. The resolving power of X-band is greater, and allows for more detailed radar images, but the shorter wavelength is more easily reflected by small objects such as waves, sea-birds, rain, etc., resulting in the appearance of so called "clutter" on the radar image display.

A marine radar is not used as a primary means for electronic position-fixing. However, determining a vessel's position using radar can be achieved by techniques such as taking range and bearing measurements from known radar-conspicuous objects, or parallel-indexing. These techniques are carried out manually and are primarily used as a fail-safe backup to conventional radio-navigation such as GNSS. To fix a vessel's position continuously using radar and plot these fixes on a navigational chart would constitute a great deal of manual effort and would not be practical on a typical commercial vessel. It may be observed, however, that the particular pattern of radar-return obtained from a particular location can be highly distinctive and unique. Experienced mariners would be able to recognise the Lizard peninsula, for example, from its radar image alone.

The GLA has investigated and developed techniques that allow a marine radar to perform absolute positioning, that is determine the latitude and longitude of own vessel using radar return information. There are two main methods of doing this: ***active*** and ***passive***.

In the ***active*** method, a response is sought from the transmission of radar information from a radar transponder, responding from a "paint" of the transponder from the ship's radar signal. Radar transponder beacons (RACONS) actively listen for incoming radar signals and respond on the same frequency to any that are detected. These beacons are highly conspicuous in a radar return and provide positive identification of a particular object. A technique has been trialled for automatic positioning using radar by equipping racons with the capability to communicate their precise location to a radar system; such modified racons are called ***eRacons***. The technique also requires upgrading a ship's marine radar to a pulse coherent radar, which while allowing lower power radars, also allows demodulation of the transmitted data. Automatic positioning using range-and-bearing data is then possible using the return signal from the eRacon. Knowing the precise location of the transponder and a single range and bearing measurement of its location, from the location of the vessel, allows the computation of the vessel's own position. Multi-lateration (and multi-angulation) from multiple transponders allows greater precision in the position solution. This technique is potentially very accurate, and is not dependent on any pre-surveying or mapping campaign.

However, there is a requirement to provide a sufficient number of such eRacons to allow high-accuracy navigation throughout a wide area.

In the ***passive*** method no such active transponders are employed, rather the pattern of the return from the natural and built environment is captured and used for positioning. The pattern may be enhanced by using passive radar reflectors installed at precise locations ashore. These passive reflectors are similar to the kind installed aboard leisure craft, and shore infrastructure, in order to enhance their response on ship's radar.

The GLA have investigated a number of techniques for developing a radar absolute positioning solution:

- ***Terrain Reference Radar Positioning*** - Compare the received images to the predicted return derived from a terrain-database, such as DTED.

- ***Radar Dead Reckoning (RaDR)*** - Perform dead-reckoning (DR)-type positioning by solving for changes in vessel position, comparing the current radar image to an earlier one taken at a known location.

- ***Surveyed Radar-Return Map*** - Create a map of observed radar-return covering the entire run, and at each epoch fix a position by comparing the received image to the map.

- ***SLAM*** – Simultaneous Location and Mapping with RaDR.

- ***Integrated-DR Technique*** – Kalman Filter Integration with other sensors such as speed-log and gyro.

Additional Dead-Reckoning sensors, such as speed-log and gyro, can be integrated into the radar SLAM solution. 'Traditional' log-and-gyro based DR shows very slow and steady error-growth over time, potentially making it much more reliable over *long-term* GNSS-outages than an inertial system based on Inertial Measurement Units (IMU), which provide better performance over the *short-term*. The aim of integration of traditional DR with radar SLAM is to constrain the error growth of a DR only solution. Once the radar SLAM based image-correlation has been used to solve for the vessel's movement over, say, the last 15-seconds, the difference between this solution and the traditional DR solution can be filtered and applied as a systematic bias-correction for the log and gyro measurements – thus maintaining the accuracy of the DR solution.

5.5 Satelles: Satellite Time and Location (STL)

STL uses a series of short data messages transmitted at 1620 MHz from a payload on the Iridium constellation of Low Earth Orbit (LEO) satellites. This data is received by the user's receiver and used to determine a position solution computed using information about the Doppler shift of the signals. While the actual approach used by STL is commercially sensitive, it is believed to follow an approach whereby a series of ranging estimates are made as the satellite moves across the sky. Generally at mid-latitudes only one satellite is in view at a time (more are visible to the user as they move towards the poles) and successive position estimates are taken as the satellite moves across the sky. These estimates are then combined to provide an estimate of the vessel's position. The movement of the vessel during the process can directly contribute to the error in the position, unless it is tracked and considered in the position estimation process. It is anticipated, therefore, that STL would be used in combination with other sensors, such as an inertial measurement unit, to correct for movement of the vessel between position estimates.

Satelles' has an exclusive commercial license to use the Boeing Time and Location technology, which uses data and frequencies previously used to support paging applications on Iridium satellites.

For STL to work, the navigation system will consist of the following components: Iridium satellites; STL Receivers; STL Ground Control Station; STL Uplink Station; STL Maintenance Centre; Data Communication Backbone and Supporting e-Navigation services. The expected architecture of the system is shown in Figure 24.

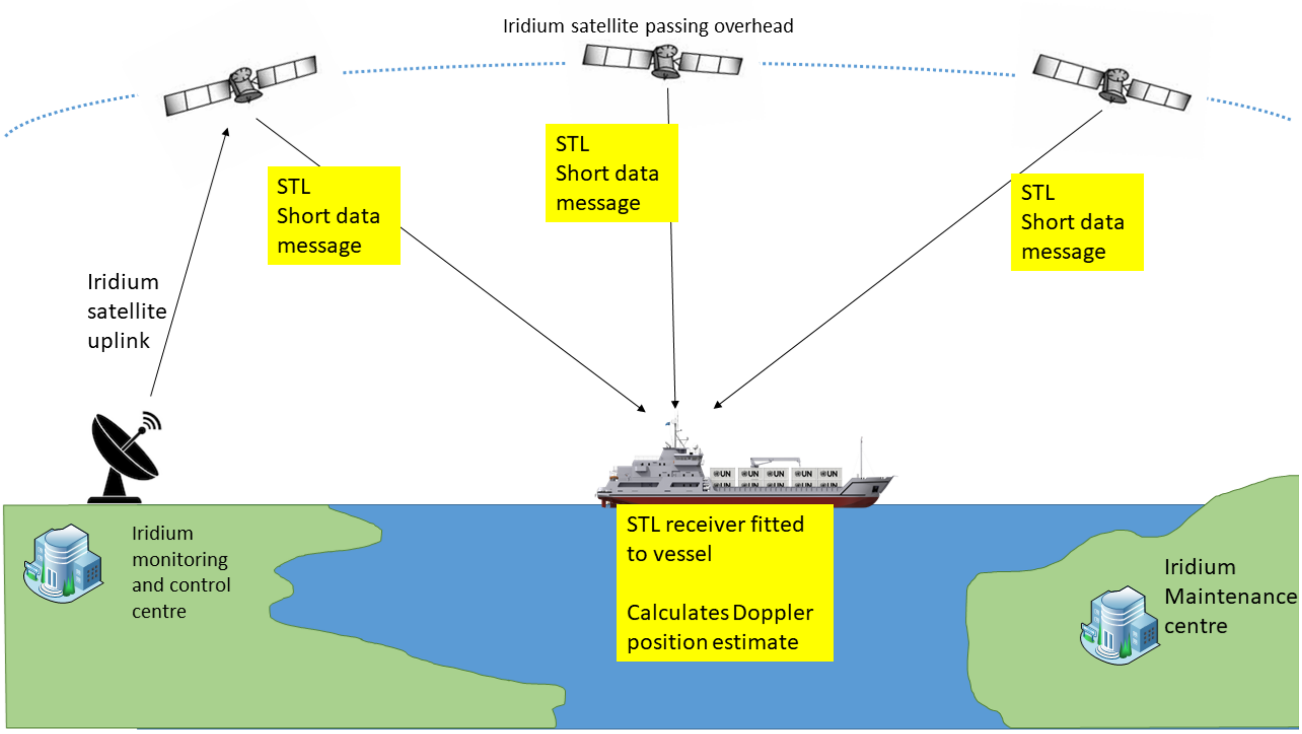


Figure 24: General architecture for STL. Note only the yellow labels are considered part of the STL service, the rest of the architecture is part of the Iridium constellation architecture.

It is noted that the service is likely to be made available on a user subscription basis. In this approach the user has no financial or management accountability for the running or maintenance of the system. The user would simply purchase a subscription to the service to suit their requirements.

While Orolia's VersaPNT Assured PNT Solution receiver offers the potential for STL integration, it is not clear whether this integration is readily available, or whether this receiver would be available to the civilian population. Given the novelty of the STL approach, it is believed that receiver development remains in the prototype stage. The STL receiver is likely to be combined with an inertial unit, or other sensors, with STL/other sensors being used to constrain the drift of the inertial device. As noted previously, the movement of the vessel needs to be tracked in order to get the best accuracy from the system, so it is unlikely that an STL component would be usable on its own. Given the unknown capability of the receiver unit at this stage it may be more appropriate to refer to it as the "STL User Equipment", as it is expected to contain more functionality than a simple receiver.

In order for an STL position to be used on a SOLAS vessel, the approach would need to be shown to meet an IMO receiver performance specification. It is unclear whether the multi-system receiver performance standard would be sufficiently broad to capture this, or whether a new IMO document would be required. Subsequent IEC test specifications would be needed to enable international type approval and would be expected to take 2 years from the start of the process.

There are many unknowns currently regarding the development of STL and what service it will provide. These include:

- Availability of the solution;
- Accuracy performance and whether the vessel's speed affects performance;
- What integrity is included, if any;
- What level of continuity is considered;
- Whether there is any risk of interference affecting performance given Iridium/STL frequency allocation not being primary in some national frequency allocations;
- Whether there is any dependency on GNSS timing, either within the Iridium constellation or any supporting infrastructure;
- What is the proposed business model for STL use? One assumes a subscription service, but this has not yet been confirmed;
- Will STL provide more than one frequency for the user?
- Will individual Doppler and ranging data be made available from the user equipment for integration with other sensors?
- Is the STL frequency within the sweep range of common jammers?

5.6 LOCATA

Locata™ is a terrestrial positioning technology that utilises a network of small, ground-based transmitters (LocataNet) providing a robust radio-based positioning signal within a specific area. To provide nano-second level synchronisation Locata uses a patented synchronisation method called TimeLoc™ that allows internal synchronisation without the need for precise oscillators such as atomic clocks. This enables the Locata network to provide accurate position solutions utilising one-way ranging signals. The technology was developed by Locata Corp, based in Australia. The Locata concept was designed to overcome the limitations of GNSS, as well as other pseudolite-based positioning systems, to provide high accuracy and reliable signals, in all environments at an affordable cost.

Locata transmitters, known as LocataLites, transmit multiple GPS-like code and phase signals, in the 2.4 GHz licence-free ISM (industrial, Scientific and Medical) band. The system provides single-point positioning, meaning that a decimetre to centimetre-level positional fix can be obtained without the need for a reference (base) station. Locata can operate on its own, but it can also integrate with external systems including GNSS or IMU.

Any terrestrial radio-based positioning technology faces hazards in the form of multipath, imprecise clocks, the near-far field effect and tropospheric delay, among others. Locata deals with these problems through a combination of hardware and signal based solutions. Time-Hopping/Direct Sequence Code Division Multiple Access, a 10% pulsing scheme (whereby transmission from each receiver is not continuous, taking turns within 1s to use the allocated 100 µs timeslots, use of an extended bandwidth and a spreading waveform with 20dB Processing gain are all employed to maintain high signal quality. Four spatially, and frequency separated signals from each Locata transponder offer very effective multipath and noise mitigation methods.

A LocataNet consists of a Terrestrial Segment (TS) and a navigation User Segment (US). The TS consists of the LocataNet, a network of LocataLite transceivers located within or around a defined service area, which provides the positioning signal. The LocataNet is made up of a **master** unit (that provides time) and multiple **slaves**. Recent changes allow to nominate backup master that takes over if the main master is unable to operate, increasing the resilience of the system. The US consists of any number of fixed or moving Locata user receivers (rovers) operating within the service coverage area. The system uses precise network time, provided by TimeLoc™, to calculate position in a GNSS-like fashion using code and carrier phase. Slave LocataLites can maintain time by synchronising with the master receiver directly, or if there is no line of sight, through other receivers using a process called “cascade synchronisation”.

Locata offers two modes of position: Code pseudorange, providing meter level accuracy; and Carrier phase fix, able to provide cm level accuracy. The system achieves position fixes in a GNSS-like fashion, using code or an integrated carrier phase (ICP). Successful 3D trilateration requires visibility of at least four LocataLites to solve for position, height and receiver clock offset. With good geometry and visibility conditions, Locata is capable of providing cm to dm (decimetre) level horizontal accuracy (dm level 3D accuracy). Exact accuracy is very dependent on the geometry and other accuracy factors such as multipath. The current implementation of Locata in the Ports of Auckland, New Zealand, that support its land-side application, is using its proprietary beam forming VRay antenna to combat multipath. The Locata system provides Positioning, Navigation and Timing information as long as the master is aligned with UTC time. Otherwise Locata time will be internally consistent but will drift away from UTC.

5.6 System-of-Systems Integration with Dead Reckoning

Integration of candidate technology options with Dead reckoning (DR) will achieve an overall hybrid system-of-systems solution. The principle is illustrated in
Figure **25**.

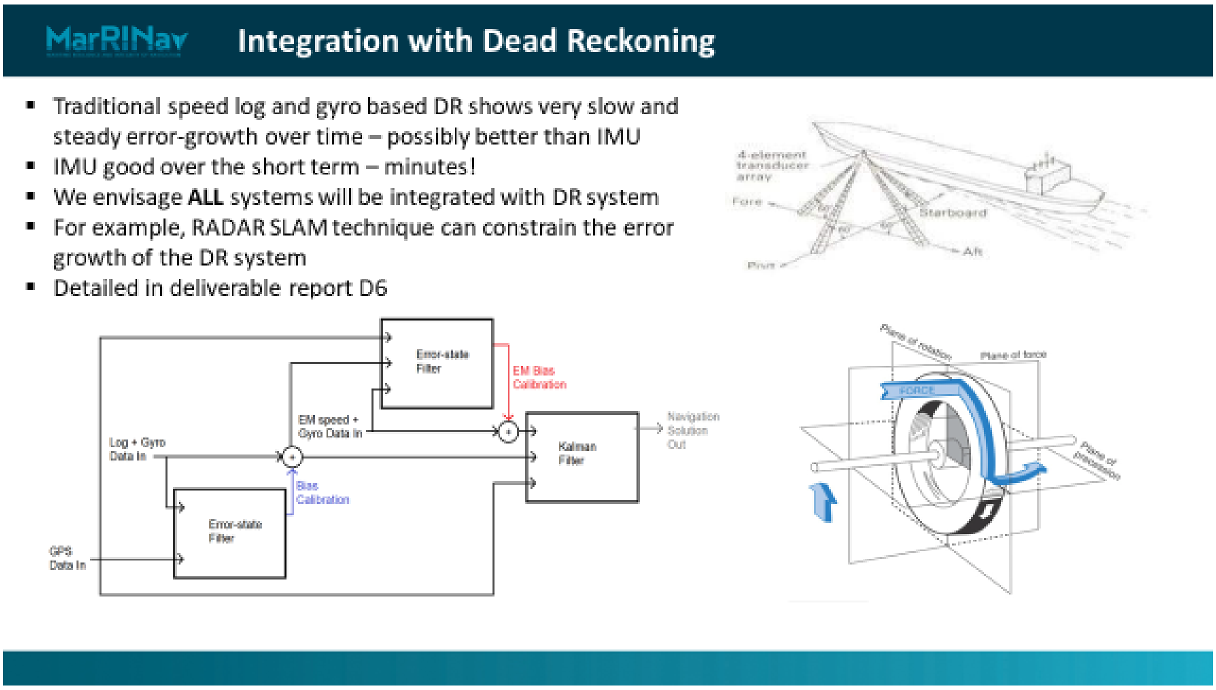


Figure 25: Principle of integration with Dead Reckoning

The importance of such integration within the IMO MSR is to maintain accuracy and availability and especially, to enhance integrity and continuity of the maritime PNT solution. Table 3 sets out a summary of accuracy performance of the candidate technologies against principal requirements.

In this table, Dead Reckoning (DR) technologies include combinations of the following:

- Doppler velocity log (DVL) and/or a 2D correlation velocity log (CVL), also known as an acoustic correlation log;
- Inertial measurement unit (IMU) used as an inertial navigation system (INS), assuming tactical grade, i.e. an IMU costing in the order of £18,000;
- Mechanical gyrocompass;
- Magnetic compass;
- Coherent radar dead reckoning by comparing successive images and/or successive range measurements to eRacons and passive targets at unknown locations.

Requirement set (arbitrary numbers)	1	2	3	4	5	6
Accuracy (95%)	1000 m	100 m	100 m	10 m	10 m	10 m
Integrity Limit with 10^{-5} risk	2500 m	250 m	250 m	25 m	25 m	25 m
Distance from coast	Any	<100 km	Any	<10 km	<100 km	Any
GNSS	Yes	Yes	Yes	Yes	Yes	Yes
Differential eLoran	No	Yes	Note 1	Yes	Note 3	No
Differential eLoran with VDES R	No	Yes	Note 1	Yes	Note 3	No
eLoran	No	Yes	Note 1	No	No	No
eLoran with VDES R-mode	No	Yes	Note 1	No	No	No
MF, VDES or MF/VDES R-mode	No	Note 1	No	No	No	No
Coherent radar ranging with DR	No	No	No	Note 2	No	No
Dead Reckoning (DR) for 15 min	Yes	Yes	Yes	No	No	No
Dead Reckoning (DR) for 3 hours	Yes	No	No	No	No	No
DR + Star Tracker	Yes	No	No	No	No	No

- Note 1: Theoretically possible, but impractical to achieve this level of coverage.
- Note 2: Subject to maturity of the technology
- Note 3: Requirements are met within 30 km of the coast, but not in the 30-100 km range

Table 3: Comparison of selected PNT technologies with various user requirements.

Figure **26** shows the proposed architecture for the dead reckoning system. Note that an expensive navigation-grade INS is not needed as continuous calibration is proposed. Tactical-grade inertial sensors should be sufficient and it may even be possible to use consumer-grade sensors. Further research is needed to determine a suitable minimum sensor specification.

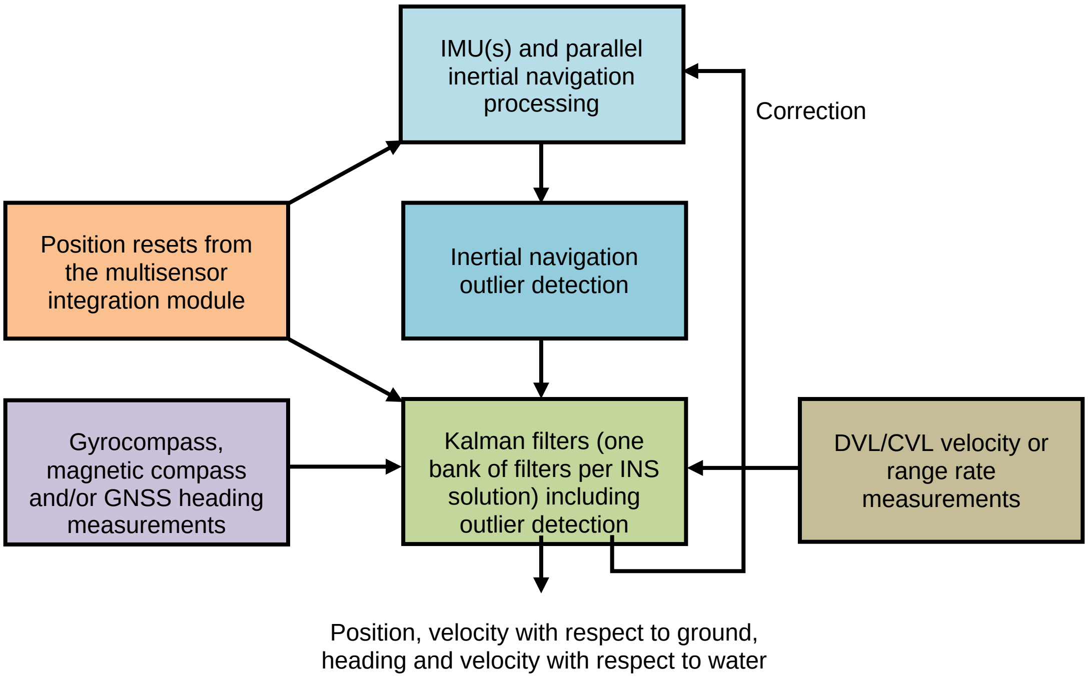


Figure 26: Proposed architecture for the dead reckoning system

Under normal operating conditions, GNSS will be much more accurate and reliable than the other positioning and navigation technologies. Integrating GNSS with other technologies, therefore risks degrading the navigation solution. Therefore, the main position and velocity solution should be provided using GNSS only with the other technologies providing heading and velocity with respect to water. Where GNSS is unavailable or degraded, the multisensor position and velocity solution should be used instead.
Figure **27** and Figure 28 respectively illustrate the proposed primary and reversionary integration architectures. A multisensor integration module is needed to combine measurements from the backup systems such as R-Mode and eLoran; this module is illustrated in
Figure **29**.

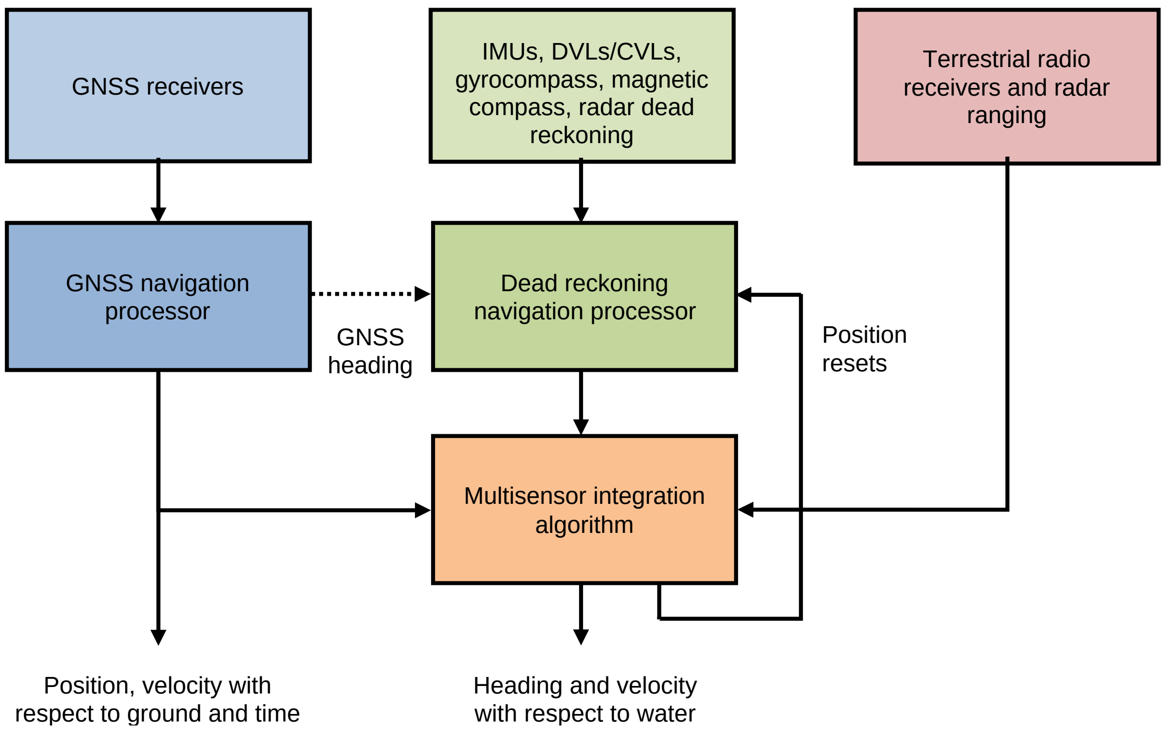


Figure 27: Proposed primary-mode architecture for resilient maritime multisensor navigation.

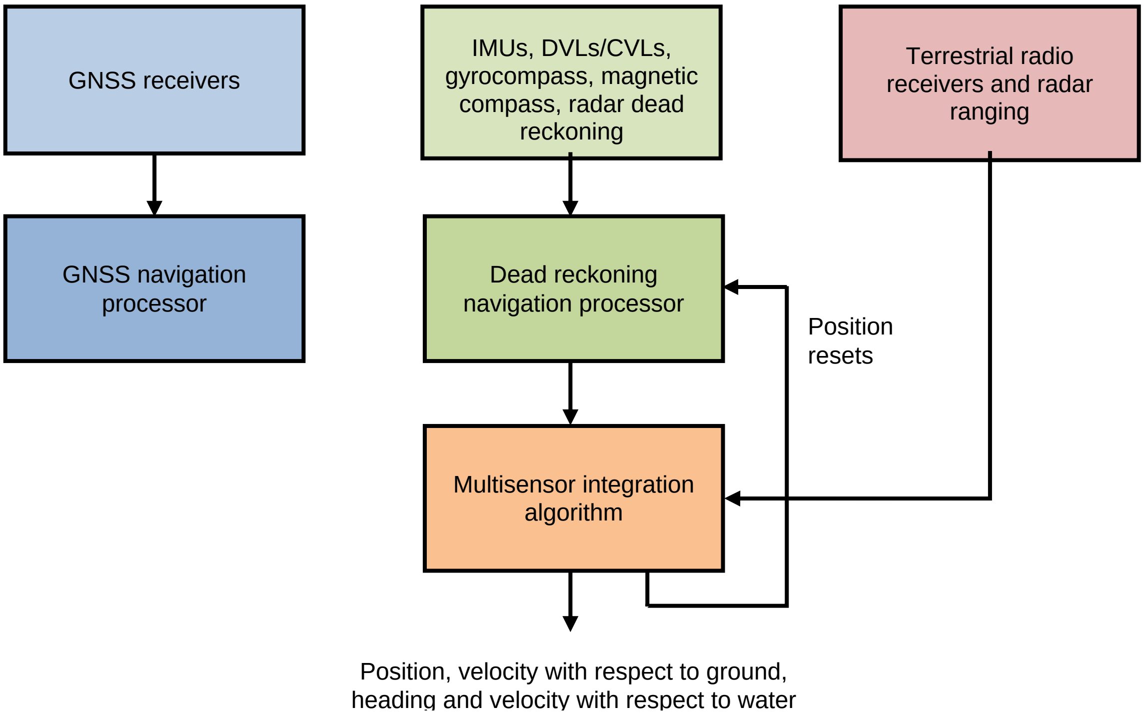


Figure 28: Proposed reversionary-mode architecture for resilient maritime multisensor navigation.

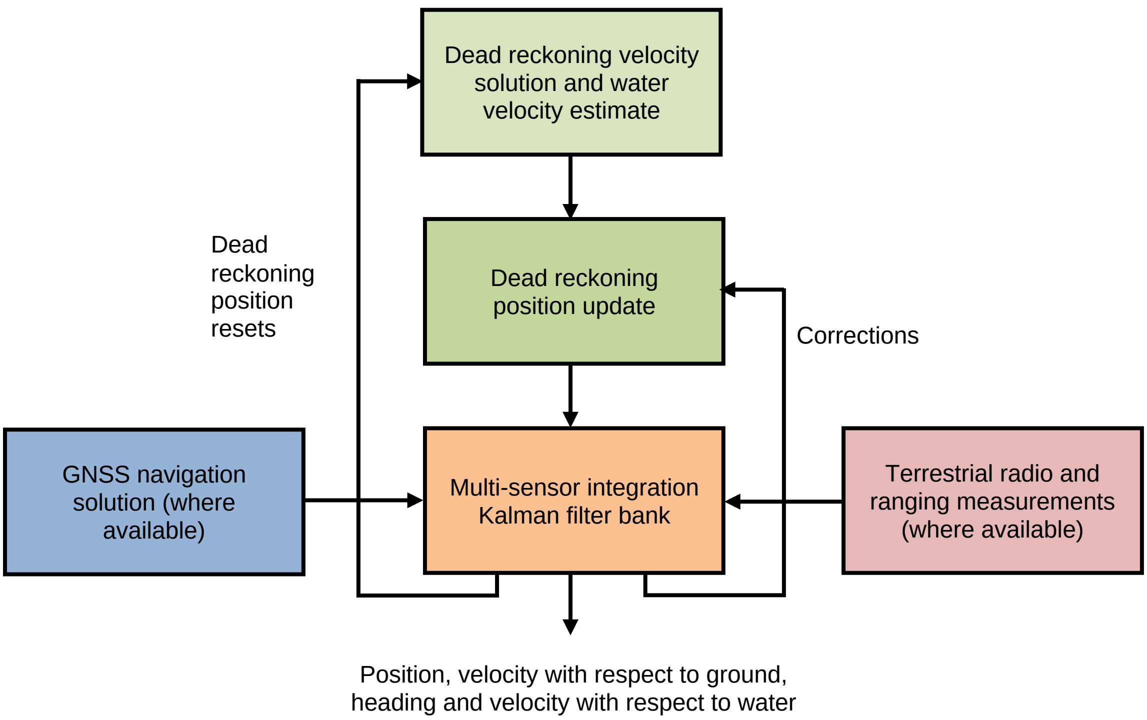


Figure 29: Proposed architecture for the multisensor integration module.

6 System-of-systems capability for resilient PNT

This section of the MarRINav study addressed the questions: Where do we put our Resilient PNT system's infrastructure to optimise coverage and performance to meet users' requirements? How will it perform? How do we control and monitor the system?

6.1 System-of-Systems conceptual architecture

The conceptual architecture of a system-of-systems has been developed to provide resilient high-integrity Positioning, Navigation and Timing (PNT) as part of UK maritime Critical National Infrastructure (CNI). The concept aims to provide suitable navigation capability during long periods of GNSS degradation or loss, for all types of commercial vessels and leisure craft, throughout the waters of the 200NM Exclusive Economic Zones (EEZ) of the UK and Ireland, as well as in ports (including land-side operations in ports). The report describes the principles of a unified shore-based conceptual architecture, which combine PNT and communications technologies to underpin future aids-to-navigation and e-Navigation services within the timeframe to 2030.

The conceptual solution considers principally UK sovereign solutions that complement GNSS (specifically GPS, Galileo and EGNOS). Terrestrial components of the architecture are geographically limited to being sited within the UK, insofar as a UK-only solution is feasible, whilst conforming to international standards and fully supporting international shipping operations within the EEZ. The architecture extends to operations in ports, with the aim of ensuring the resilience and integrity of PNT across the land/sea interface in the logistics chain. A further objective is that the conceptual solution should also have the potential to contribute to robust PNT capability for land transport and many other applications in the diverse UK sectors impacted by GNSS vulnerabilities.

The solution is described as a conceptual geographic (physical) architecture of a system-of-systems (Figure 30) and as a conceptual operational architecture, with a common basis for terrestrial systems (Figure 31). It considers a combination of terrestrial radio navigation systems that are independent of GNSS, dissimilar and complementary. These systems are primarily the relatively mature technologies of eLoran and LOCATA, the less mature Ranging Mode (R-Mode) of the VHF Data Exchange System (VDES) and the emerging capability of ships' radars to derive absolute positioning from imaging of the coastline.

Just as GPS performance varies fundamentally with physical factors (e.g. number of satellites, geometry of the user's sightlines to satellites, signals' propagation delays through the earth's atmosphere and radio noise environment at the receiver), terrestrial radio navigation depends similarly on the number of transmitters, their locations, transmission paths and reception of their signals. The siting of shore-based transmitters is crucial to the resulting reach and area coverage of the resilient PNT service that can be achieved by the maritime CNI.

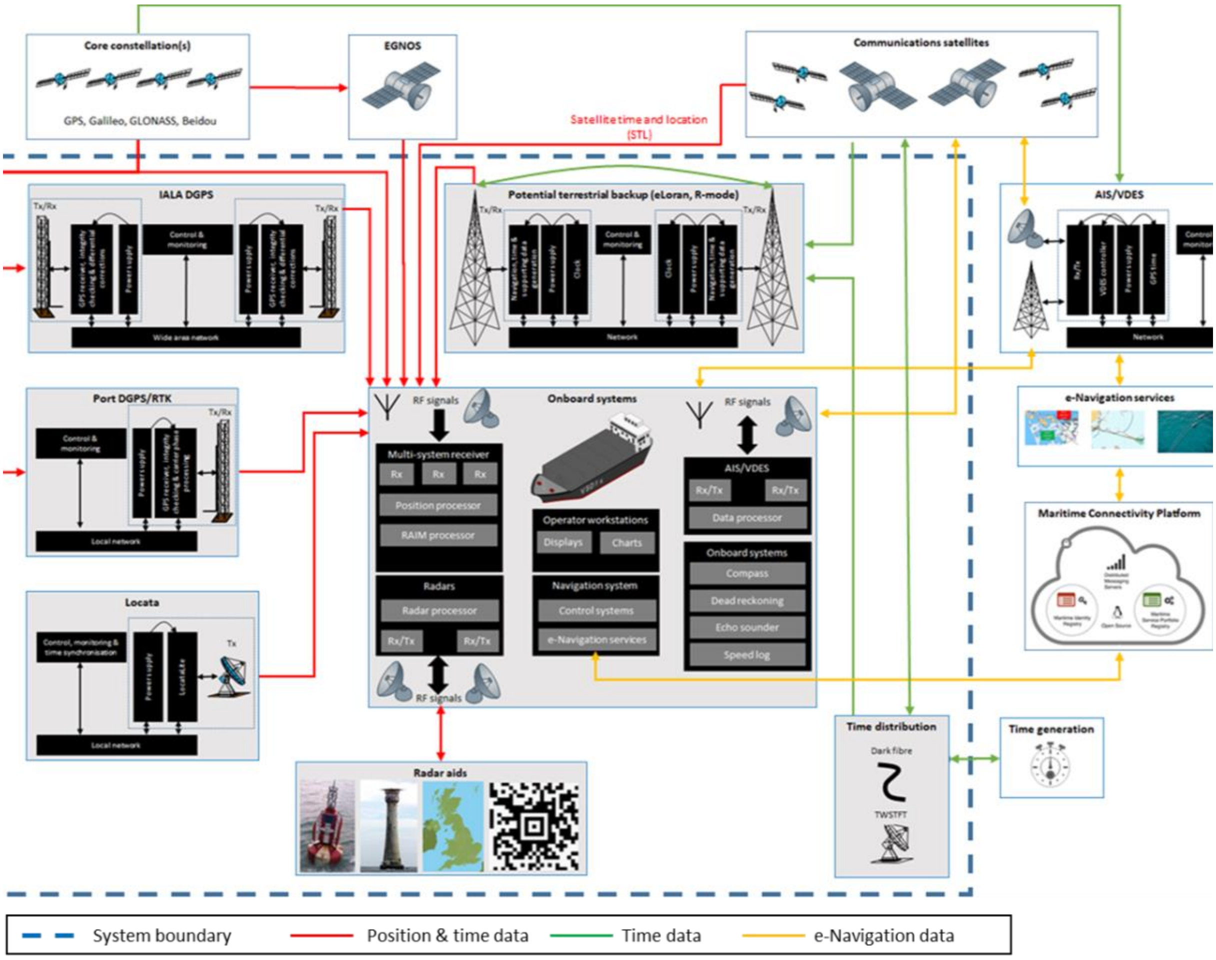


Figure 30: Conceptual architecture for resilient maritime PNT and associated systems.

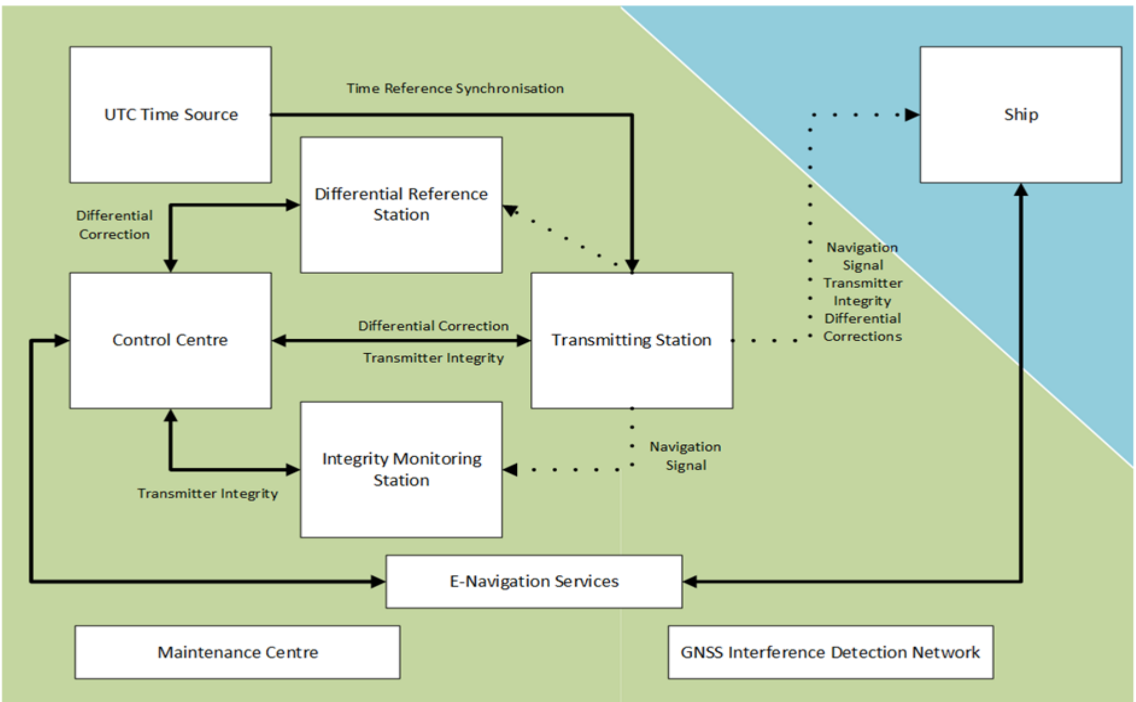


Figure 31: Common conceptual architecture for terrestrial systems.

Hence the geographic architecture of transmitters is crucial in providing the user with appropriate signals to establish sufficient positioning accuracy and integrity over as wide a coverage area as possible. This applies to all radionavigation systems that use the signal's time of arrival to determine position, to wide area systems such as eLoran, regional area systems such as VDES R-Mode and local area systems such as LOCATA.

Within the present MarRINav analysis, siting of eLoran transmitters has been determined judiciously to maximise both PNT service coverage and cost-effectiveness. This is achieved through the use of locations with existing TV mast infrastructure in the UK, capable of accommodating current operations simultaneously with relatively low power LF transmissions, and by maintaining the existing high-power installation at Anthorn. In the case of VDES R-Mode, sites have been selected predominantly at a subset of existing AIS station locations that would be expected to be upgraded to VDES in due course. A few additional VDES R-Mode stations have been considered where the degree of navigational risk indicates a need for extension of the service coverage area.

The hybrid system-of-systems PNT solution also follows the principle of primarily using the wide area eLoran system for maximum overall geographic coverage, then supplementing with regional VDES R-Mode and/or radar absolute positioning to fill capability gaps in the wide area coverage. This approach generally results in PNT capability being delivered chiefly by each system standalone within the limits of its specific coverage area. Where more than one separate PNT solution is available, they can then be combined in the ship's Multi System Receiver (MSR) as a loosely-coupled (or tightly-coupled for wider coverage) integrated navigation solution. This combination of the systems provides the user with the overall best estimate of the vessel's position, with a level of integrity, availability and continuity that is better than each individual system.

6.2 eLoran performance and coverage

The positional accuracy performance of a UK only eLoran system, using the existing Anthorn transmitter and 5 additional new transmitters at TV mast sites, is shown in Figure 32. The UK eLoran coverage is better than 10m (95%) at 9 out of the 10 most major UK ports and many coastal areas achieve better than 20m (95%). However, the port and straits of Dover, together with the north-eastern approaches to the Channel, are less adequately covered. Coverage can be extended into these more challenging areas if eLoran transmissions were to be resumed from the Sylt transmitter station in Germany. The effect of the addition of Sylt transmissions is shown in Figure 33.

Figure 34 shows the predicted timing precision coverage available from eLoran transmissions from Anthorn. In the plots, the dark blue contour represents the boundary of the regions covered by better than 100 ns timing precision capability. The other contours shown are 200 ns (light blue), 500 ns (green) and 1000 ns (dark red). The left hand plot assumes an internally mounted antenna no differential-Loran, but a one off ASF calibration at any location. The right hand plot assumes an externally mounted antenna with differential-Loran, but a one-off ASF calibration at any location.

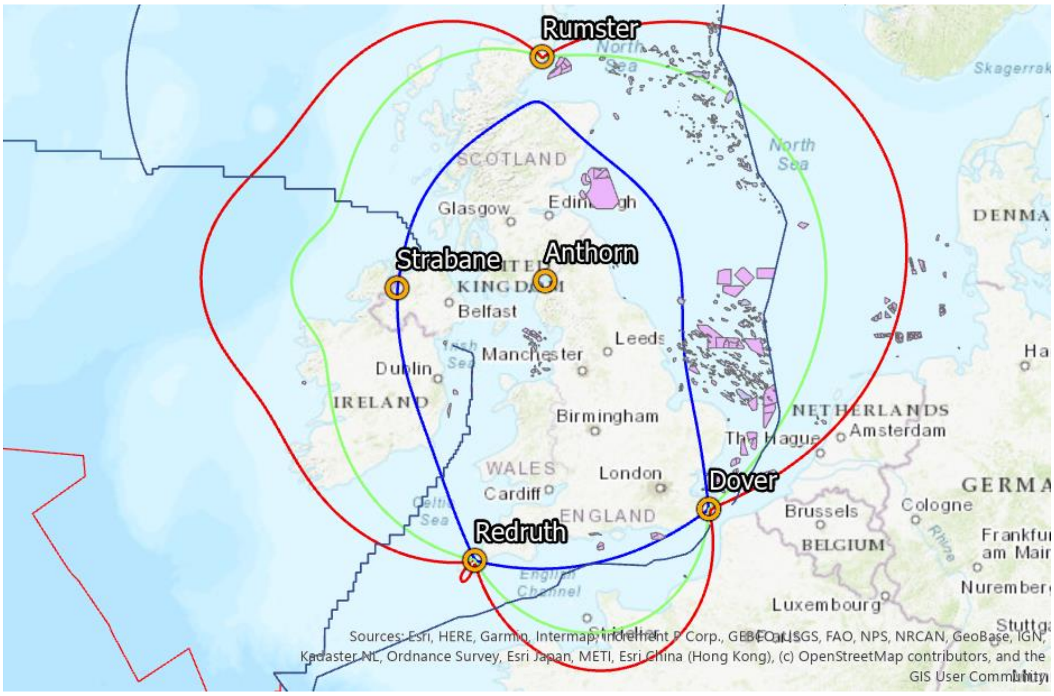


Figure 32: MarRINav GIS plot showing accuracy coverage contours of UK based eLoran. Blue = 10 m (95%), Green = 20 m (95%) and Red = 30 m (95%).

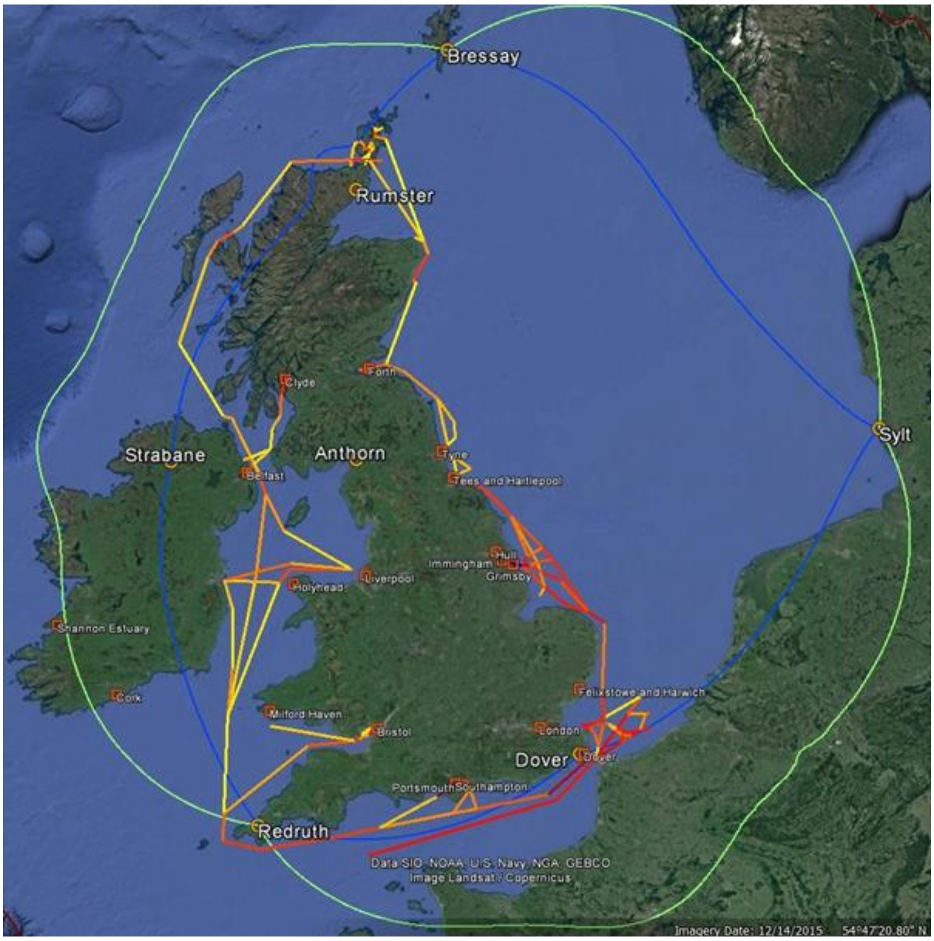


Figure 33: eLoran accuracy coverage contours UK plus Sylt (Germany).

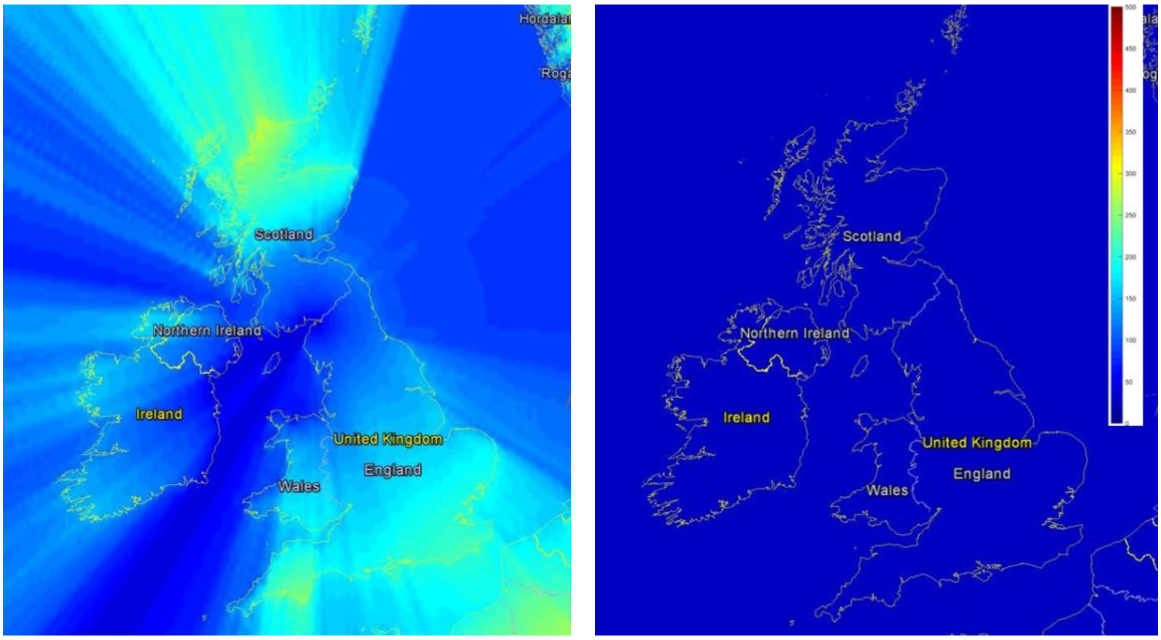


Figure 34: eLoran precise Timing coverage across the UK and Ireland

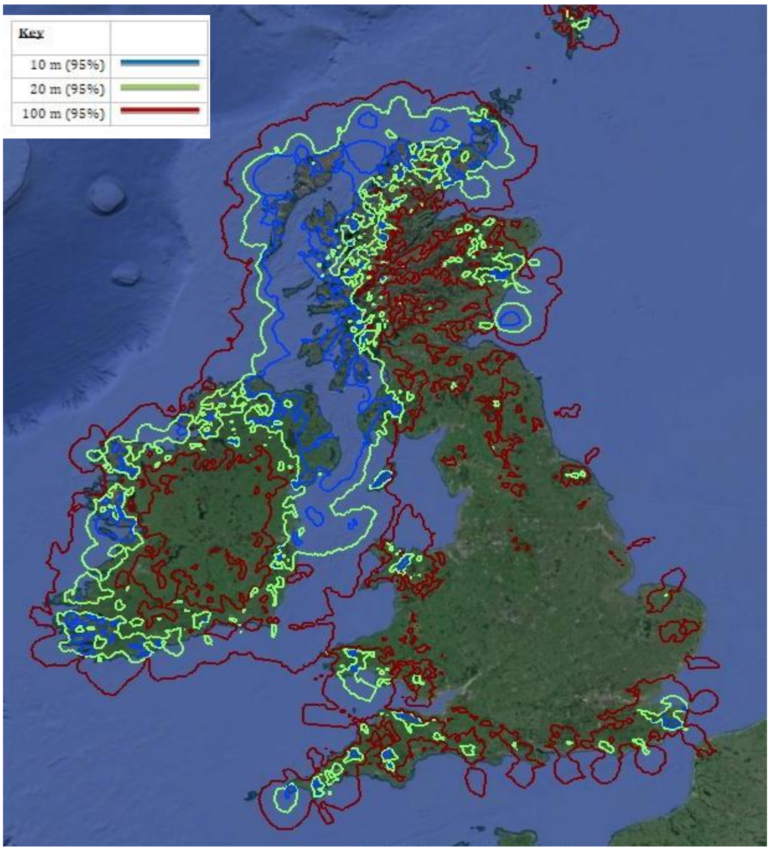
6.3 VDES R-Mode performance and coverage

Figure 35 shows the VDES R-Mode positional performance coverage based on the locations of existing UK and Irish AIS stations upgraded to VDES with R-Mode (the R-Mode Baltic Sea method with 3 stations required at each location at sea around the coastline). Three coloured contours are shown that represent 10 m (blue), 20 m (green) and 100 m (dark red) 95%'ile accuracy.

It can be seen that coverage on the West coast of Scotland, South Wales, the far south-west (Lands' End) and North of the Forth Estuary is at the 10 m level in parts. The system in the English Channel is able to meet the 100 m IALA Coastal Voyage Phase recommended requirement in small patchy areas. However, it can be concluded that, using the assumptions above, the simple conversion of existing UK AIS stations to VDES and adding R-Mode capability to mariners' receivers is ***not*** sufficient to provide adequate, uninterrupted coverage around the UK coastline.

In Figure 36 we have included converted AIS stations at Dungeness in the UK and Calais, Dunkirk and Gris-Nez in France and added prospective VDES stations at Sheerness and the conveniently located Royal Air Force base at Bradwell, both in the River Thames Estuary. We can see that in both respective regions the 10 m contour (and therefore the 20 m contour) are pulled out further into the stations' respective areas of coverage.

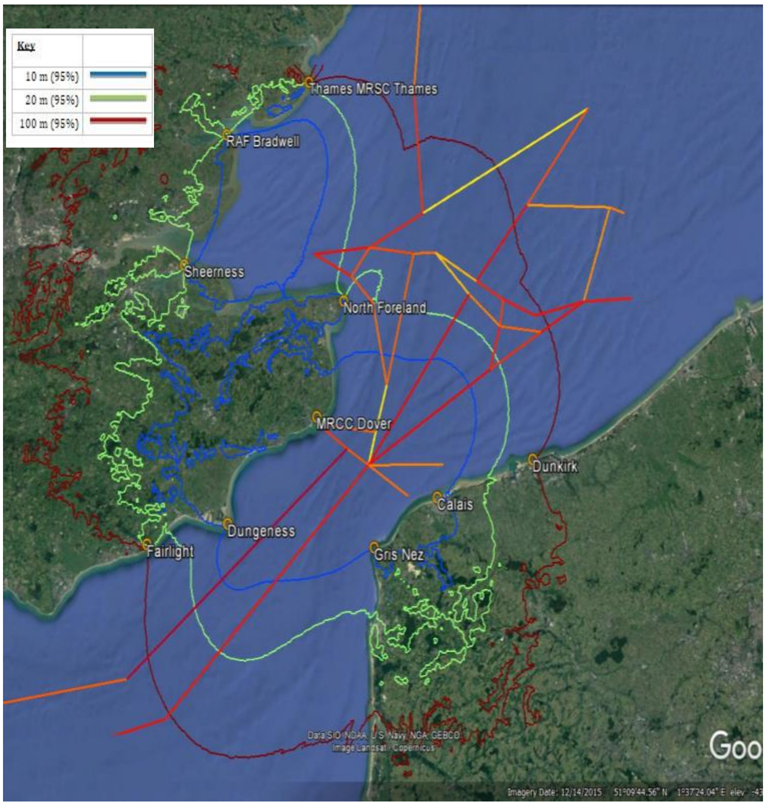
RAF Bradwell and Sheerness have created a 10 m region of coverage in the Thames Estuary, while Dunkirk has pulled coverage north from the Dover Strait, and Gris-Nez, in combination with the station at Dungeness, has pulled 10 m coverage south along the Channel.



Good performance when the stations are on the outside of the coverage area looking in but more limited performance where the stations are on the inside of the coverage area looking out, especially at Dover

VDES R-mode based on the current AIS network provides no benefit in the critical eLoran coverage gaps

Figure 35: AIS stations give a potential platform for VDES R-mode



Additional stations in the UK and France

Thames Maritime Rescue Coordination Centre (MRCC), RAF Bradwell, Sheerness, North Foreland, Dover MRCC, Dungeness, Fairlight

Gris Nez, Calais, Dunkirk

Figure 36: VDES R-mode with additional stations around Dover.

6.4 Integrated VDES R-Mode and eLoran

Figure 37 illustrates the results of a tightly coupled integration for a position solution based on the use of all measured pseudoranges, whether from eLoran (transmitters in UK only) or from VDES R-Mode, in a single position solution computation. This integration of VDES R-Mode with UK eLoran results in a greater region of coverage at the 10 m (95%) level, and even more so up to 20 m (95%). The extended coverage is a result of employing the more distant eLoran transmitters, and their contribution to the transmitter geometry with the VDES R-Mode stations. This coupling method provides a degree of redundancy of RPNT in this critical maritime region and confers significant advantages. A vessel can travel to and from the Port of London, and through the Dover Strait, with performance at the 10 m (95%) level. Passenger ferries and Roll-On Roll-Off (RORO) cargo vessels can traverse the Calais to Dover route with better than 10 m (95%) accuracy. Traffic from the Traffic Separation Scheme (TSS) region to the north-east can converge and diverge safely supported by resilient PNT in the region.

It should be noted that this configuration of UK VDES R-Mode and three VDES R-Mode stations in France coupled with UK eLoran delivers capability across the whole width of the Channel / La Manche. It confers substantial mutual benefit for the UK and France, co-operatively serving shipping throughout the national waters of both maritime administrations.

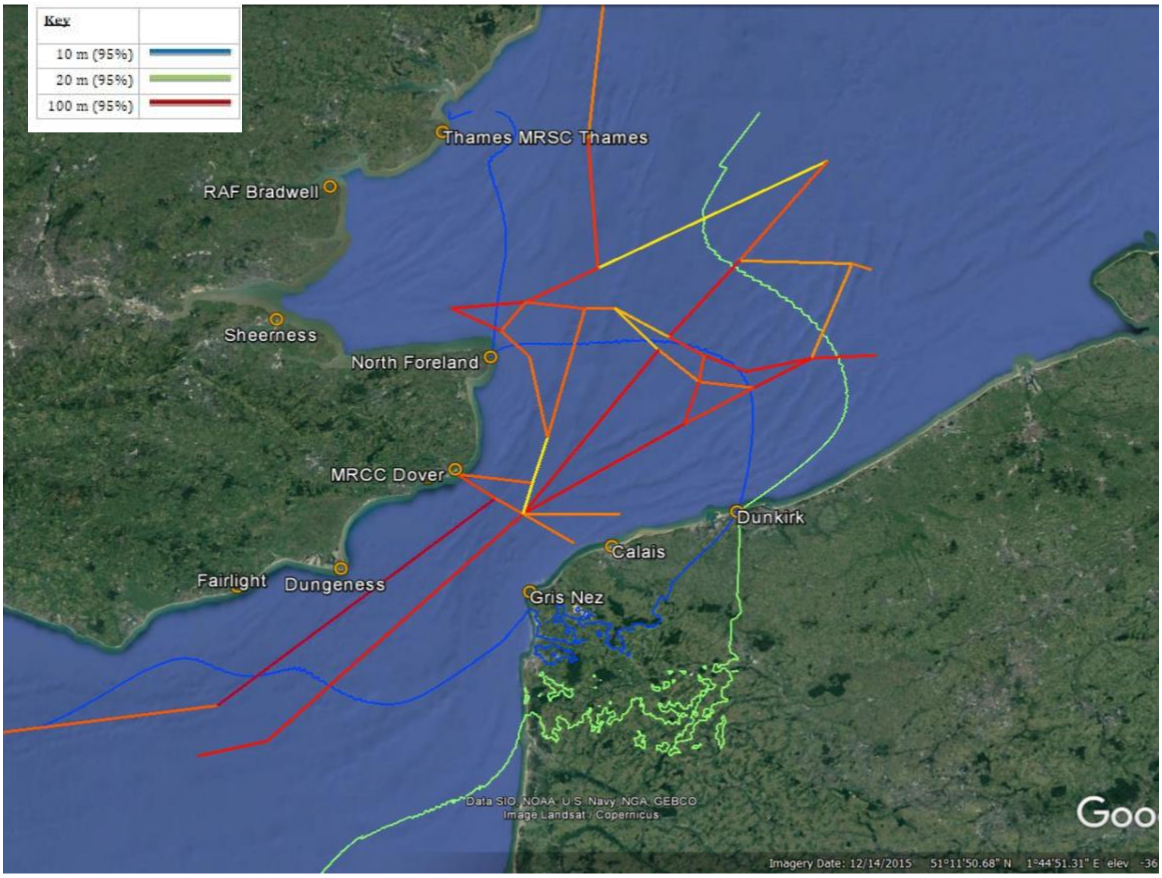


Figure 37: Coverage of Tightly Coupled VDES R-Mode and UK-only eLoran.

6.5 Conclusion for UK Resilient PNT coverage

Six eLoran transmitters are proposed to comprise a UK-only baseline eLoran system. Only one of these needs to be high power and that can be achieved by fully re-establishing the eLoran facility at Anthorn. The remaining five transmitters are proposed to be much lower power and distributed widely towards the extremities of the UK land mass. These transmitter sites are the locations of existing TV masts capable of hosting additional LF transmissions using an innovative method of using the mast's supporting infrastructure. There is one lower-power eLoran transmitter site identified in each of Shetland, Northern Ireland and Scotland, with a further two located at the east and west extremities of southern England.

The resulting UK baseline eLoran provides extensive coverage of maritime positioning capability for the UK at either the 10 metres or 20 metres (95%) accuracy level. The 10 m accuracy performance covers most of the UK coastline and 9 out of 10 UK major ports (considered by economic value of goods in transit). Dover is an exception and needs further intervention. Coverage at 20 metres (95%) position accuracy covers a substantial part of the UK EEZ. This baseline covers many of the areas of highest navigational risks of collision or grounding.

With international cooperation, the UK baseline eLoran system could be extended significantly with the use of a single additional transmitter in mainland Europe. In particular, analysis has shown that re-establishing the Loran transmissions from Sylt in Germany (and upgrading that location to eLoran) would greatly extend the coverage to the east across the UK EEZ, notably including the Port of Dover and its environs. It is noted that Loran infrastructure at Sylt, although mothballed and not currently transmitting, remains in place and renewed eLoran transmissions would be feasible alongside others planned for that site. Extension of eLoran coverage to a wider area of the Irish EEZ would be possible by the addition of a single further low-power transmitter in the south west of Ireland, nominally at Mizen Head. This would provide a baseline Irish resilient PNT capability, in particular covering the Shannon ports and the Port of Cork.

The UK-only baseline eLoran system leaves some gaps in capability at just one major UK port, the Port of Dover, and at three key areas of higher navigational risk: the Dover Straits, the TSS to the north-east of Dover and in the vicinity of the Pentland Firth and Orkney Islands. This is clearly unacceptable for such important maritime areas and hence regional systems (VDES R-Mode and radar absolute positioning) must be considered within the hybrid PNT solution for these areas, to maximise the coverage a UK sovereign solution (entirely under UK control) while conforming to international standards.

Analysis of the potential deployment of UK-only VDES R-Mode stations alone has been found insufficient for positioning capability at the Port of Dover, Dover Straits and the TSS to the north-east. However, it would be feasible and of mutual benefit in this high risk area for the UK to cooperate and synchronise with VDES R-Mode transmissions from France, deploying VDES R-Mode on both sides of the Channel. The strategic, policy and economic implications of such cooperation with France have not been considered in this stage of the project, although it is noted that R-Mode currently appears as a prime candidate for maritime PNT backup technology within the EC's draft Implementation Plan to progress the resilient PNT solutions of the European Radio Navigation Plan (ERNP). The ERNP has been influenced by the development of R-Mode in the Baltic region, for which such a solution has reasonable coverage due to many of the sea areas being enclosed by land in relatively close proximity.

The inclusion of just three VDES R-Mode stations in France, along with the UK VDES R-Mode baseline, has been predicted to provide satisfactory positioning coverage at the 10 metres (95%) level for the whole of the Dover Straits and the Port of Dover. The most challenging UK maritime area in which to achieve satisfactory resilient PNT coverage is the TSS area (and its approaches) to the north-east of Dover, arguably one of the highest risk maritime areas in the world. This capability gap can be almost completely closed to the 20 metres (95%) level by the hybrid solution of closely coupled UK eLoran with VDES R-Mode (including three French VDES R Mode stations).

A hybrid PNT solution coupling VDES R-Mode (including just 3 stations in France) with UK eLoran provides performance at the 10 m (95%) level for the Port of Dover, the Dover Straits and much of the TSS region to the north-east, with a large area of the Channel covered at the 20 m (95%) level.

UK VDES R-Mode and 3 VDES R-Mode stations in France, coupled with UK eLoran, confers substantial benefit for the UK and France across national waters of both maritime administrations.

7 Cost Benefit Analysis

7.1 Scenario activities and assumptions

The CBA considers the central economic case of maritime transportation and assumes that one 5-day wide area outage of GNSS will take place within the next 10 years, with certainty. The analysis focusses on a scenario with container ships only, based on the activities listed in

Table 4. The economic assumption is drawn upon a selection of 10 major ports, which handle 90.5% of the economic value attributable to maritime transport of containers. The resilient technologies are selected in order to fully enable maritime traffic around these ports in the absence of GNSS. The benefits are computed by taking the difference of economic loss from an outage of GNSS between a situation with a resilient System-of-System (SoS) based on non-satellite-based sources of position, navigation and timing, and no change from the current scenario. Costs are estimated with respect to the selected technologies, the amount of necessary infrastructure, and the number of ships considered.

Scenario of Container Ship and Cargo Transfer - Activities
Activity 1 – Vessel is making way in ocean phase
Activity 2 – Vessel approaches UK coastline, entering coastal voyage phase
Activity 3 – Vessel arrives at anchorage, or a pilot station (if pilot required)
Activity 4 – Vessel enters port approach voyage phase (w or w/o pilot)
Activity 5 – Vessel enter port phase and manoeuvres
Activity 6 – Vessel arrives at berth
Activity 7 – Vessel's cargo is cleared and unloaded by crane
Activity 8 – Container is collected and transported to the stack
Activity 9 – Cargo container is loaded onto truck for departure from port
Activity 10 – Truck makes way through port and exit port gate

Table 4: Activities of the scenario.

The maritime sector cannot, however, be viewed in isolation as it depends on land transport operations to move the goods to the end-user (or, symmetrically, to the vessel). For this reason, the CBA must consider the land transport system as part of the analysis. Disruptions to land transport mean there is a (lower) upper limit for the benefits that can be saved by the MarRINav SoS. However, MarRINav has identified that the RPNT SoS, in particular the inclusion of eLoran, can also contribute to resilient PNT solutions for land transport and Timing applications.

In this analysis, we estimate the costs associated with the creation of a resilient navigation SoS and compare it with the benefit it would provide to the maritime industry and wider UK society. The benefits are the loss avoided due to a GNSS outage, whilst the costs are those of implementing and maintaining such SoS. The study has been carried by independent economists and engineers of the maritime sector, using best practice to build the assumptions of the CBA. The reader should bear in mind the following limitations and caveats:

- Not all the economic value is captured by the scenario. It is approximated using container ships as they carry the largest economic value in and out of the UK. For this purpose, we also restrict the loss of economic value to a share less than the £1.1bn estimated in the GNSS loss report.
- A national, resilient system is difficult to establish as each port and maritime zone have different characteristics and, therefore, one-size does not fit all. We identify one major port as a proxy for the whole UK.
- The knowledge about the readiness of some alternative PNT technologies is uncertain. The CBA assumes that the technology is ready when it is required.
- We assume that the total economic value at stake is constant over time and that the probability of the disruption to occur is uniformly distributed over time.

7.2 Benefits

As 69% of the economic value transits through containers in the UK, the overall value attributable to containers amounts to £601m. We define 'value loss' as the economic value at stake due to a GNSS outage. We compute it by superimposing an efficiency loss to the economic value attributable to containers.

Table 5 illustrates the efficiency loss and the economic value at stake for each of the activities in the scenario due to GNSS outage with no resilient PNT SoS in place.

	Activity									
	1	2	3	4	5	6	7	8	9	10
Efficiency loss	15%	60%	40%	70%	70%	70%	100%	100%	100%	30%
Values loss (£m)	90.2	360.8	240.6	421.0	421.0	421.0	601.4	601.4	601.4	180.4

Table 5: Estimation of the value loss given the efficiency loss without MarRINav.

Maritime transportation would be hit by the maximum loss of efficiency. If the port cranes stop working, unloading does not occur and therefore the cascading effect will induce delays and even freeze operations in major ports. The below figure illustrates the value loss due to GNSS loss. The blue area shows the proportion of economic value remaining in each activity (independently from the others) and the red lines show the cumulative efficiency.

Applying the same methodology, we can estimate the value loss with MarRINav technologies available to provide resilient PNT during the GNSS outage, achieving the improved efficiencies shown in

Table 6. With a resilient PNT SoS, better efficiency is achieved in all but one activity. The MarRINav SoS enables the ships to be fully operable and the bottleneck effect is pushed back to the truck operations in Activity 10.

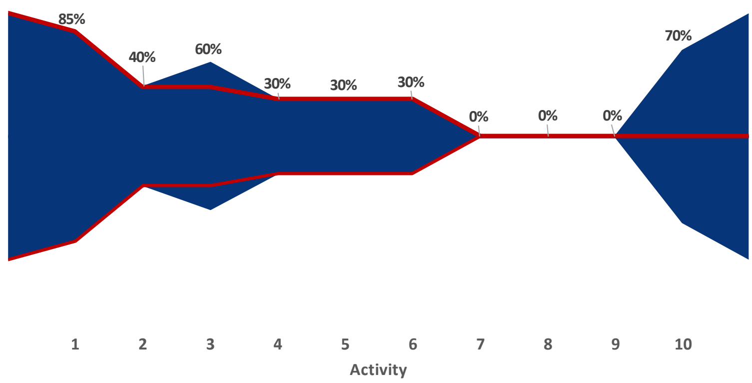


Figure 38: Bottleneck effect induced by a GNSS loss, without resilient PNT.

	Activity									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Efficiency loss	0%	0%	0%	0%	0%	0%	0%	0%	0%	30%
Values loss (£m)	0	0	0	0	0	0	0	0	0	180.4

Table 6: Estimation of the value loss given the efficiency loss with MarRINav.

The benefits from MarRINav are the consequence of the development of a SoS capable of maintaining maritime operations. Without this RPNT SoS, the total economic loss is **£601m** whereas, with the MarRINav SoS , the total loss is reduced to **£180m**. Under our assumptions, the total economic value saved is **£421m.**

7.3 Costs

The global number of vessels at the end of 2018 was approaching 60,000. The number of container vessels represents slightly less than 9% of the total number of ships, i.e. approximately 5,200. The ships' equipment is required on any vessel that intends to approach UK ports. We assume that all ships are likely to trade in (or transit by) the UK at least once a year and therefore, all container ships will be equipped with the necessary equipment.

We split the costs into two categories namely ashore infrastructure costs and shipowner costs.

Table 7 details the infrastructure required on land. The present value of costs for onshore technologies is **£80m** over 10 years.

System	CAPEX (£'000)	OPEX (£'000/y)	Units
eLoran			
eLoran Transmitters	4,000	250	6
eLoran control centres	1,000	100	2
Differential loran reference stations	60	3	10
Integrity monitor stations	3	3	1
ASF surveys	31	Negligible	10
Radar absolute positioning			
eRacon	30	Negligible	12
VDES-R module			
Conversion AIS station to VDES	50	Negligible	10
LOCATA			
LocataLite	30	Negligible	1,050
Rover	10	Negligible	700
Control centre	Update existing	Negligible	10

Table 7: Costs of ashore infrastructures per unit.

Table 8 gives a summary of onboard technologies alongside the capital and operational expenditures. Overall, the investment cost per ship is equal to **£23,000**. The marginal operational expenditures are negligible. Therefore, the costs to shipowners is only an upfront investment. In total, the cost to shipowners is close to **£120m**, in one year. It brings the total cost for MarRINav to **£200m over 10 years**.

System	CAPEX (£'000)	OPEX (£'000/y)	Units
eLoran			
Marine eLoran receiver	1	Negligible	5,200
Radar absolute positioning			
IMU	18	Negligible	5,200
GNSS-compass (included in IMU)	Negligible	Negligible	5,200
VDES-R module			
VDES receiver	1	Negligible	5,200
ePelorus			
ePelorus	3	Negligible	5,200

Table 8: Costs of on-board equipment per ship.

7.4 CBA results

Given the information above, and as shown in

Table 9, the net present value of the MarRINav system-of-systems is positive and equal to £221m. This is equivalent to a benefit-cost-ratio of **2.2**. Under our assumptions and for **5,200 container ships and 10 major ports**, these results indicate that the investment in a resilient solution is highly beneficial to the wider society.

Benefits and costs	Value (£m)
Benefits (avoided loss)	**421**
Loss without MarRINav	601
Loss with MarRINav	180
Costs	**200**
Costs of ashore infrastructures	80
Costs to shipowners	120
Net Present Value	**+221**
Benefit-cost ratio	**2.2**

Table 9: Summary of benefits and costs.

The results also show vast differences between the beneficiaries. We can distinguish four groups of stakeholders: the government, port operators, ship owners and the wider society (industry, manufacturers, etc.). These differences are highlighted in
Table 10. Wider society captures most of the benefits from MarRINav (**95%**) while incurring no costs at all. The shipowners have limited benefits and carry **60%** of the costs. The remaining costs are split between the Government and port operators (**20%**) each. This asymmetry indicates a need for **financial redistribution** as rational shipowners and port operators would be unlikely to implement MarRINav on their own initiative. It is beyond the scope of this report to propose a suitable mechanism for redistribution.

Benefits and costs	Benefit	Cost	NVP
Government	0	41	-41
Port operators	19	39	-20
Ship owners	2	120	-120
Society	399	0	421

Table 10: Summary of benefits and costs, by stakeholder group.

Wider benefits can be expected as well. The inland infrastructure deployment could be useful to other sectors than maritime transportation. Some of these technologies may be applicable in road transportation, which could improve that sector’s robustness. Further analysis would be required to determine the technical viability and suitability of using the services designed for maritime on the road. Additionally, users outside the transport domain, including the financial and telecoms sectors, may benefit from access to the timing service required to operate MarRINav. Such benefits have not been assessed.

The estimates in this report show that a resilient System-of-Systems can mitigate the adverse impacts of a loss GNSS in the maritime domain. The MarRINav project has been defined to identify a unifying solution for the UK maritime sector, but it is reasonable to consider whether subsets of the solution can or should be implemented in isolation.

An obvious candidate is to implement a solution that mitigates against the loss in Activities 7-9, namely port container handling. These activities would become very inefficient in the absence of GNSS (and MarRINav), but the identified solution – Locata – could be implemented at comparatively modest costs.

Introduction of Locata would generate benefits of **£180.4m** (£601.4m less £421.0m, see table 10 for details). The associated costs would be **£38.5m** (see table 11), yielding a Net Present Value of **£141.9m** and a Benefit-Cost Ratio of **3.7**.

8 Outline Development Plan and Roadmap

8.1 Outline Development Plan

An Outline Development Plan forms the core of the proposal for a future Phase 2 of the MarRINav project. The primary aim is to implement a test-bed demonstrator to prove the concept of the hybrid system-of-systems solution at a local scale and to demonstrate its effectiveness for a variety of users (not confined to maritime). Outputs from the test-bed demonstrator will support future decisions on the possible design and implementation of a resilient PNT architecture for CNI at UK national scale, encompassing but not limited to maritime applications. It should do so by proving the concept to be cost-beneficial to the diversity of users and applications, both in maritime and other sectors, and by reducing the technical risk of the systems and their integration at scale.

The Outline Development Plan identifies proof-of-concept activities over a nominal timeframe of at least two years, based on research and development (R&D) steps for individual technology maturation and the implementation of a **physical** system-of-systems **test-bed** demonstrator on a local scale. This will be supported by a modelling and **simulation test-bed** to provide insights for its physical realisation and to predict performance results at national scale. The five stages of the Outline Development Plan are:

1. **Planning**: confirmation of objectives, elaboration of a detailed plan, specification of requirements and location assessment for the test-bed demonstrator.

2. **Design and Development**: maturation of technologies within the system-of-systems solution, and modular design of the systems-of-systems following systems engineering principles.

3. **Software Test-Bed**: models of technologies and prediction of hybrid service coverage areas to support physical demonstration and validation from real-world results.

4. **Physical Test-Bed**: implementation of bare-bones demonstrator for proof-of-concept of the hybrid PNT solution.

5. **Demonstration**: tests and trials at sea and in ports, with ships carrying prototype receivers and operating in a variety of maritime signal reception conditions.

The results of the demonstration would inform UK policy for a UK national solution to resilience of maritime PNT, addressing the recommendations of the Blackett Report and the £1B economic loss attributed to the maritime sector in a 5 days disruption to GNSS analysed in the London Economics report. UK policy decisions at Cabinet Office level, supported by the UK Space Agency PNT Strategy Group's consideration of the PNT demonstration results, could determine the implementation of the demonstrator's recommended system-of-systems at national scale.

The philosophy of the test-bed development process is to build incremental development of each system's technological maturity (i.e. increasing their TRLs) before integration as a system-of-systems, implementation within the test-bed, trials & evaluation, demonstration and overall assessment to prove the concept. This development concept is illustrated in Figure 39, which shows the test-bed demonstrator growing as the component technologies are matured and the supporting infrastructure is developed and included.

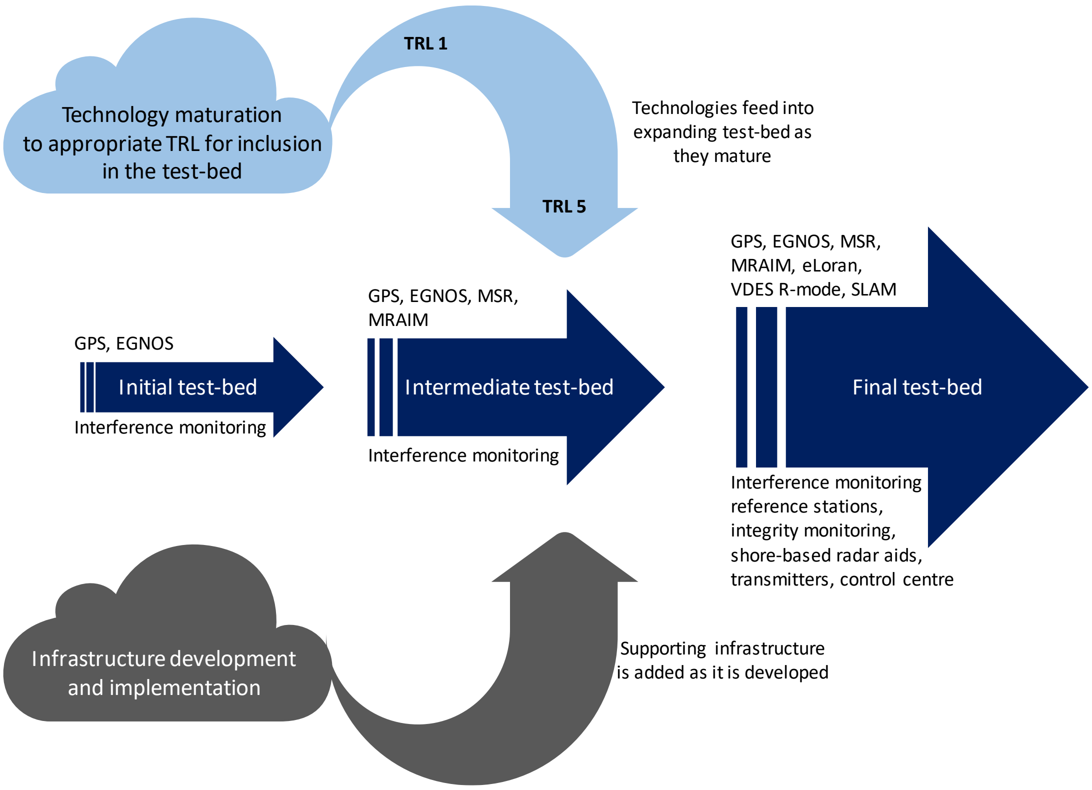


Figure 39: Test-bed demonstrator growth concept.

The end-to-end development process is illustrated in Figure 40 below. There are four main stages to the development process:

1. The **planning stage**, which will produce the detailed plan, including objectives, the tasks to be undertaken, timeframes and milestones, expected outcomes, risks and mitigations, resource requirements, dependencies and success factors. This stage will also identify and formalise the requirements for the test-beds. The location for the test-bed will also be selected, based on a set of criteria established to ensure that the test-bed results are representative so that lessons can be learnt.

2. The **design and development stage**, which will take the requirements and build on the conceptual architecture to create a design with sufficient detail to form the basis of the software and physical test-beds. For each of the component PNT systems the

design will specify the functions to be performed within each of the conceptual building blocks.

3. The **software test-bed**, which will design, implement, test and utilise models of the system-of-systems at component, individual system and system-of-systems levels. The software test-bed will be designed and implemented so that refinements can be made to the models as real-world results become available for validation.

4. The **physical test-bed**, which will be built in incremental phases to the design as technologies reach sufficient maturity. The physical test-bed will likely start with GNSS, EGNOS, eLoran and LOCATA and build further as VDES R-mode and radar positioning are developed. Initial demonstrations will be made at the individual system level to test specific functions, such as time transfer using eLoran. Outputs from the software test-bed will be used to develop the physical test-bed as long as there is sufficient confidence in the validity of the software models. As additional technologies are developed, they will be evaluated at their own system level and incorporated into the evolving (partial) system-of-systems. Ultimately, the test-bed will comprise a fully integrated, complete system-of-systems.

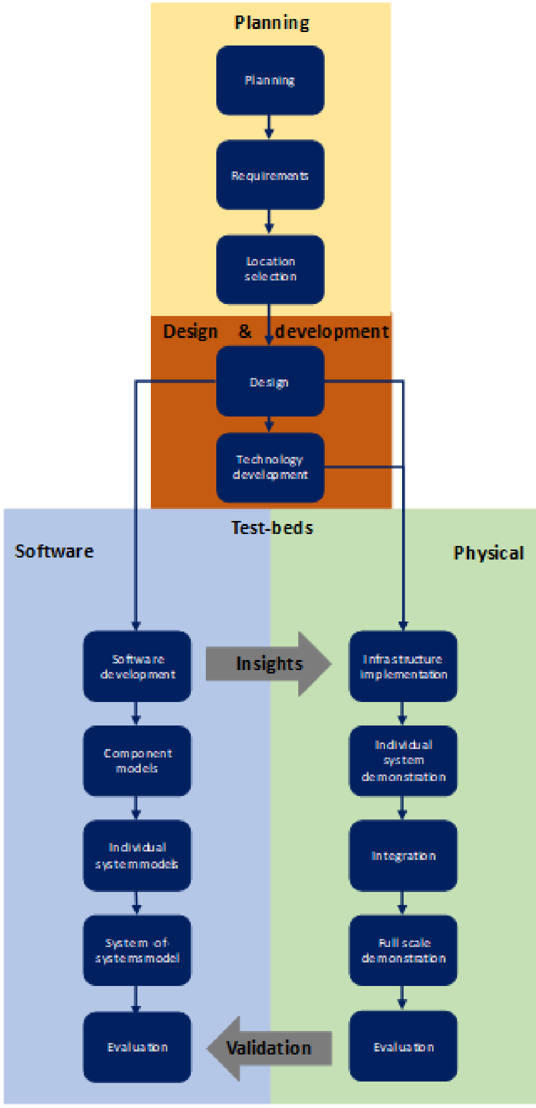


Figure 40: Development process.

8.2 Roadmap

The objective of the roadmap is to identify future priorities, gaps, opportunities, and capabilities out to 2032 that will underpin the UK critical national infrastructure (CNI) relating to maritime Position, Navigation, and Timing (PNT). The 2032 date was chosen as it takes us beyond current GLA technology roadmaps, with the next updates expected to go out to 2032+. The roadmap identifies activities that cover tangible outcomes such as technical design, implementation, and validation of the solution. It also looks at the less tangible aspects of implementation from the stakeholder, user, policy, regulatory/legal frameworks, institutional, economic and cost factors.

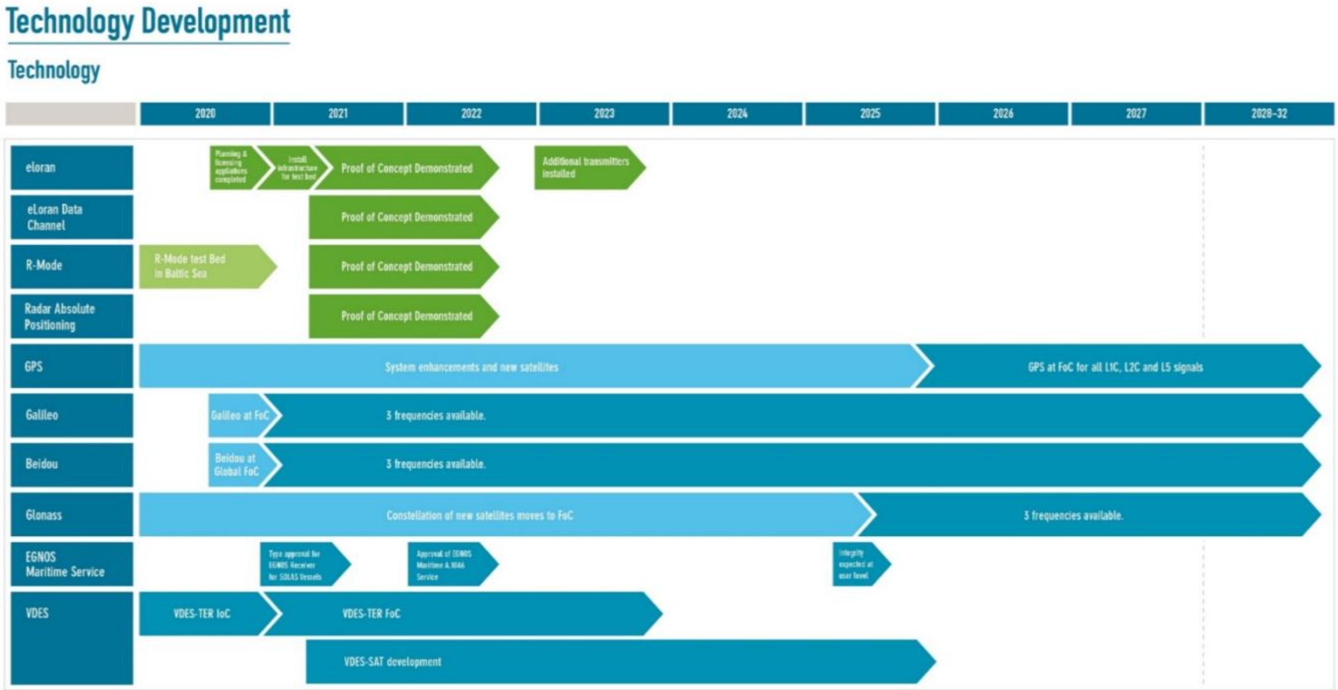


Figure 41: Technology Development Roadmap.

The roadmap of technology development is shown in

Figure 41. The roadmap of technology standards is shown in

Figure 42. The roadmap of emerging technology is shown in
Figure **43**.

A PESTLE analysis has been conducted of external factors influencing the future MarRINav direction and interaction with roadmaps. Perhaps the most significant is the societal impact. With 95% of all UK imports arriving by sea, it is hard to overstate the importance of maritime shipping. Our ability to move goods and people into and out of the country in an efficient manner is vital to the economic and social welfare of those living in the UK. Our society is our ultimate end user and how much they are willing to trust in new technologies, such as autonomous vessels, depends on our ability to achieve our goals. We must also be cognisant of how changing attitudes to climate change and pollution at sea impact voter trends and consumer demands. However, it may be possible to have some influence here as high integrity, resilient PNT will improve safety of life, not just at sea but in road and rail transport, as well as lower the environmental impact of shipping through more efficient routing.

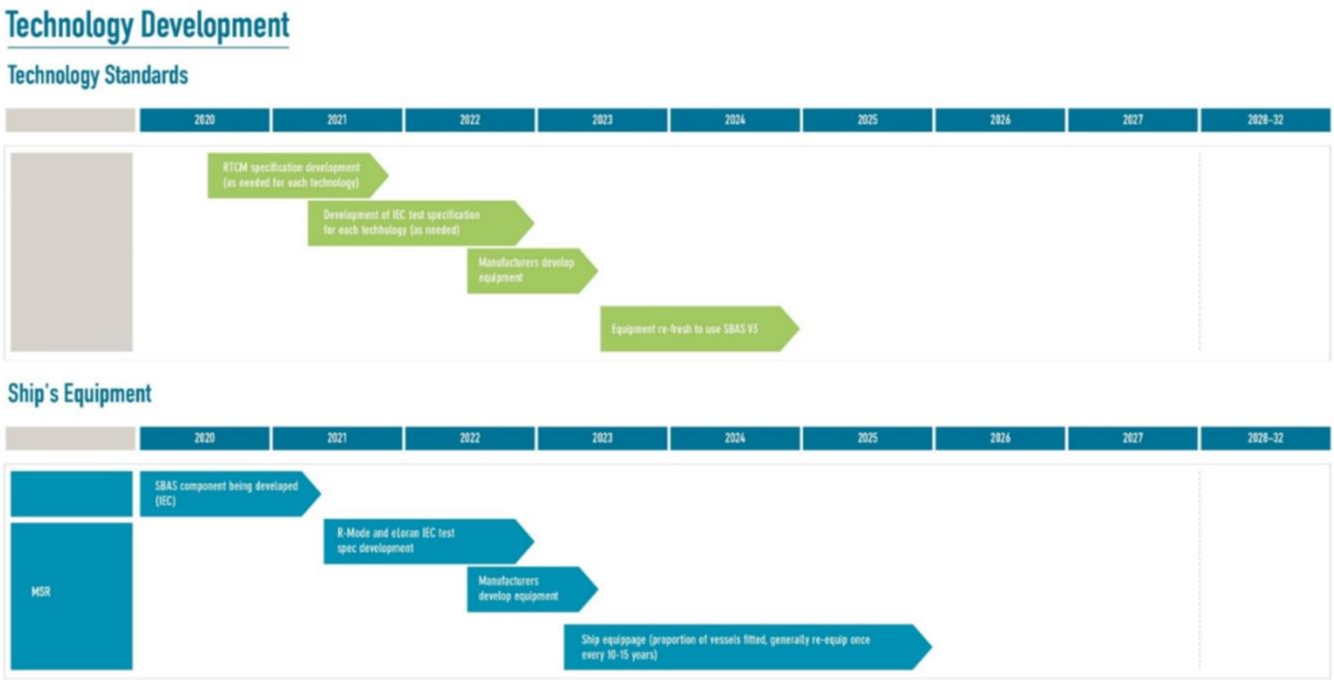


Figure 42: Technology Development Roadmap: Standards and Ship's Equipment.

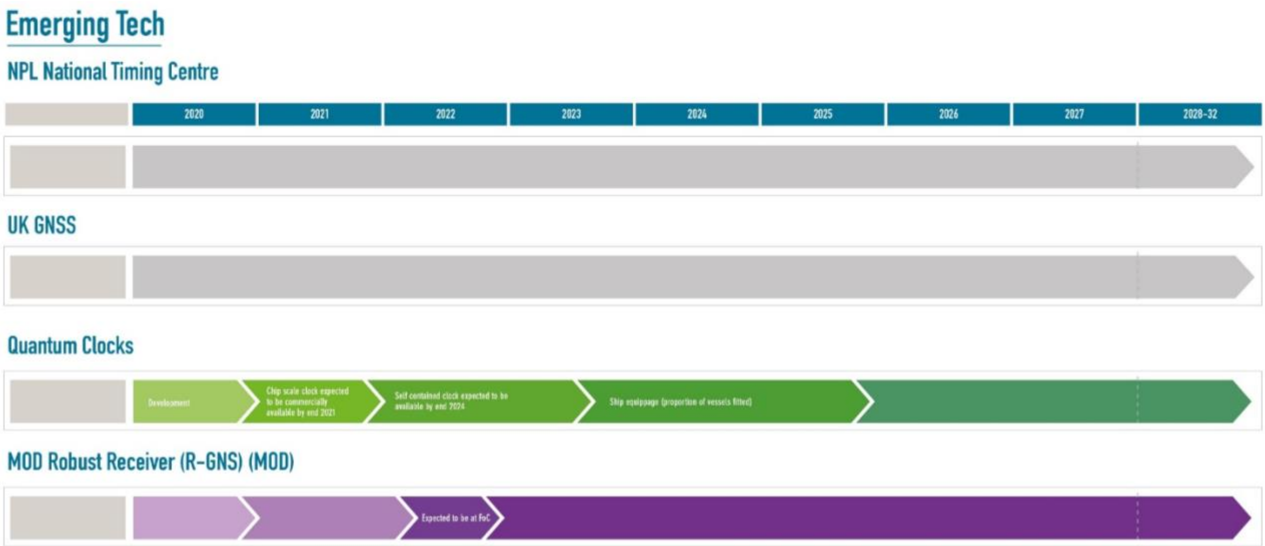


Figure 43: Emerging Technology Roadmap.

9 Summary and Conclusions

From a technical and infrastructure perspective MarRINav intends to move forward with Phase 2 in 2020. This will be a demonstrator project that will create a core high-integrity, R-PNT system with a suitable transmitter and communications infrastructure as early as possible. The demonstrator will prove the capability of this system during a trial period of 2 years, culminating with the acceptance of an initial operating capability of terrestrial high-integrity R-PNT. This will then form the foundation on which to build the full operating capability, with costs being refined over time.

Success, though, is not just a function of technology development. Strong leadership, political will, and a clear vision are also required to bring about the necessary collaborations to ensure the UK CNI has a successfully implemented resilient, high-integrity, PNT system in the 2032 timeframe. Funding of key programmes, initially front loaded by government for R&D, demonstrator projects, and infrastructure is required. It is expected that this funding will transition to private enterprise as technologies and systems mature.

Perhaps the biggest challenge to progress maritime resilience and integrity solutions is the collaboration required across multiple organisations across multiple sectors. The MarRINav team will not be acting alone and will look to public, private and third sector organisations to play their role in ensuring the resilience and integrity of the UK critical national infrastructure relating to maritime and port PNT are underpinned with an appropriate network of systems taking account of international practice by 2032.

MarRINav therefore makes the following recommendations:

1. Create a wide-reaching consensus for the future development of a resilient and high-integrity PNT system-of-systems, meeting the needs of the future UK CNI.
2. Identify an appropriate source of funding to enable the MarRINav project be progressed to Phase 2, to build on the conceptual solution, adding design detail, and undertake field-scale proof-of-concept demonstration.
3. Engage further with legislators, regulators, standards agencies, industry bodies and manufacturers.

References

[1] 'IMO A.915 - Revised Maritime Policy and Requirements for Future Global Navigation Satellite System (GNSS)', IMO, Resolution A.915(22), Jan. 2002.

[2] 'Worldwide Radionavigation System', IMO, Resolution A.1046(27), Dec. 2011.

[3] J. O. Klepsvik, P. B. Ober, and M. Baldauf, 'A Critical Look at the IMO Requirements for GNSS', ION GNSS 20th International Technical Meeting of the Satellite Division, Sep. 2007.

[4] A. Grant, P. Williams, N. Ward, and S. Basker, 'GPS Jamming and the Impact on Maritime Navigation', Journal of the Royal Institute of Navigation, Apr. 2009.

[5] '4C offshore'. [Online]. Available: www.4coffshore.com.

[6] 'Allianz Global Corporate and Speciality, Safety and Shipping Review', 2018.

[7] 'IMO Resolution MSC.401(95)', International Maritime Organisation, MSC.401, Jun. 2015.

[8] 'Guidelines for Shipborne Position, Navigation and Timing (PNT) Data Processing', International Maritime Organisation, MSC.1/Circ 1575, Jun. 2017.

[9] 'GNSS Vulnerability and Mitigation Measures', IALA, Recommendation R-129 Edition 2, Dec. 2008.

[10] 'Enhanced Loran (eLoran) Definition Document', International Loran Association, Version 1.0, Oct. 2007.

[11] J. Safar, 'AIS/VDES R-mode Development', GRAD, General Lighthouse Authorities, RPT-29-JSa-18, Aug. 2018.

[12] A. Grant, 'R-Mode update - Review of activities over FY16-17', General Lighthouse Authorities, RPT-12-AJG-17.

[13] 'R-Mode Baltic - Baseline and Priorities Report', V0.1, Mar. 2019.

[14] 'International Convention for the Safety of Life at Sea (SOLAS)', International Maritime Organisation, 1974.

Project Manager
Richard Greaves
Richard.greaves@nlaltd.co.uk

Registered office: Mill House Farm, Blackthorn Hill, Blackthorn, Oxfordshire OX25 1TJ
Registered in England: 10801372