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MarRINav

MARITIME RESILIENCE AND INTEGRITY OF NAVIGATION

Executive Summary Report

25th March 2020

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MarRINav – Maritime Resilience and Integrity in Navigation

Executive Summary Report

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Glossary

CBA	Cost Benefit Analysis
CNI	Critical National Infrastructure
DGPS	Differential GPS
EC	European Commission
EEZ	Exclusive Economic Zone
EGNOS	European Geostationary Navigation Overlay Service
ESA	European Space Agency
GLA	General Lighthouse Authorities of the UK and Ireland
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IEC	International Electrotechnical Commission
LF	Low Frequency
M-RAIM	Maritime Receiver Autonomous Integrity Monitoring
MSR	Multi System Receiver
PNT	Position, Navigation, and Timing
RAIM	Receiver Autonomous Integrity Monitoring
RIMS	Reference and Integrity Monitoring Stations
R-Mode	Ranging Mode
SBAS	Space Based Augmentation Systems
TEU	Twenty-Foot Equivalent
TSS	Traffic Separation Scheme
VDES	VHF Data Exchange System

1 The need for robust maritime navigation

Shipping is essential to the UK economy, as 95% of all imports and exports are transported by sea. Around 500 million tonnes of cargo are handled by major UK ports each year and growth trends in the maritime sector have been driving change in navigation requirements. The number of vessels in the world fleet increased to around 90,000 in 2018. Ship size is increasing, on average by 20% overall since 2011. The size of larger ships has increased faster than this: 30% increase for tankers and 32% increase for container ships. The largest lift-on lift-off (lo-lo) vessels (such as OOCL Hong Kong) are now over 400 metres in length and can carry over 21,000 twenty-foot equivalent (TEU) containers. This increase in ship size, together with a larger global fleet, is predicted to result in a doubling of seaborne trade by 2030.

Traffic complexity and density is increasing in the waters around the British Isles. Already complex and crossing traffic patterns are also constrained by the rapid increase in non-navigation marine users competing for sea space, such as offshore renewable energy installations. The majority of vessels are concentrated on the same tracks when following the most economically advantageous routes. In busy areas of dense tracks, such as the Dover Straits, vessels will also follow each other with minimal separation within designated shipping lanes. The safety, efficiency and environmental protection associated with shipping and port operations is leading to the need for increased management of sea traffic and the growing importance of resilience and high integrity of positioning, navigation and timing (PNT).

GPS has become the primary marine aid-to-navigation and source of PNT information, with physical aids such as lighthouses and buoys remaining important but secondary. Yet, GPS and all other GNSS are vulnerable to natural interference, deliberate jamming and spoofing. Trials with the Trinity House Vessel 'Galatea' in the North Sea have demonstrated how degraded GPS can produce hazardously misleading information for erroneous vessel positions without an alarm being raised. When GPS becomes unavailable, many of the ship's systems will alarm, increasing stress and workload for the bridge crew. This raises the risk of human error, even for the most well-trained mariners, when facing such challenging conditions.

THV *Galatea*

As ships' systems become increasingly digital, with the introduction of a wide range of supporting e-Navigation services and the emergence of autonomous vessels, the accuracy, integrity, continuity and availability of PNT data is critical. The International Maritime Organization (IMO) has introduced a performance standard for maritime navigation equipment to address this need, based on multi-constellation GNSS (GPS and Galileo), space-based augmentation systems and terrestrially based PNT systems, all combined in a 'Multi-System Receiver' (MSR).

2 'MarRINav' project objective and approach

Phase 1 of the 'MarRINav' (Maritime Resilience and Integrity of Navigation) project, funded by the European Space Agency (ESA), aimed to research the concept of a UK maritime critical national infrastructure (CNI) to provide resilient high-integrity PNT for ships and ports. The project's objective was to identify candidate technologies, both space-based and terrestrial, and their integration into a system-of-systems for operations across the sea/land logistics chain. The resulting maritime PNT architecture should enable robust hybrid navigation solutions to be determined by ships' onboard MSR equipment and by systems handling cargo in ports.

The MarRINav solution aims to cover an extensively wide area for shipping within the Exclusive Economic Zones of the UK and Ireland, but necessarily focuses on certain locations with highest risk of collision or grounding, together with the approaches to the top 10 major ports of the UK. It should satisfy a positional accuracy requirement for 95% of position errors to be less than 10 metres for ships approaching port and with an overall backup accuracy of better than 20 metres elsewhere, covering long periods when GPS is degraded or denied. Integrity and continuity of navigation is also essential for safe and efficient operations, with timely warnings raised when navigational errors exceed an acceptable magnitude.

Whilst complying with international regulations and standards, the architecture for PNT resilience should as much as possible use terrestrial elements located on UK sovereign territory, operated as UK CNI under national control. The solution should wherever possible not rely on radionavigation signals originating from other nations, unless commitments to their future continued operation were to be guaranteed by suitable international agreement. This stipulation inevitably constrains the physical dispersion of radionavigation transmitters and the geometry of received signals on a ship, where navigation performance is more limited if the directions from the ship to transmitters are not well spread over 360 degrees.

Recognising the limitations of existing marine radiobeacon transmissions of Differential GPS (DGPS), safeguarding of GPS-based accuracy and integrity on ships, MarRINav has considered future integrity as primarily based on Satellite-based Augmentation Systems. This implies use of the European Geostationary Navigation Overlay System (EGNOS) providing information on both GPS and Galileo for UK and Irish maritime regions within the 2030 timeframe. As the GPS signal reception environment on ships is challenging with radio noise, multipath and satellite obscuration, local signal effects will require mitigation by advanced Receiver Autonomous Integrity Monitoring (RAIM) implemented in the ship's receiver (MSR). RAIM should also extend to the backup technologies to protect the integrity of the hybrid navigation solution.

3 'MarRINav' findings on integrity of Navigation

The analysis of performance of current EGNOS V2 capability aimed to investigate the accuracy and continuity of augmented maritime navigation solutions within the western extremities of the UK and Irish EEZs. These sea areas are in the outermost expected coverage of the EGNOS 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', which the EC plans to introduce in 2022 for integrity at system-level across the extensive coverage of the EEZs, but rather to investigate the western limits of service coverage. The analysis was performed using an EGNOS model calibrated for maritime service and found two mechanisms that affect performance in this 'edge of coverage' area, both of which may merit further investigation:

- The constraints of locating EGNOS's ground reference stations (RIMS) on available land reduces their capability to provide coverage of augmentation in the outer areas of the EEZ. This could marginally affect the continuity performance of maritime navigation solutions. If this were to manifest itself significantly in practice, improvements may need to be considered with the possible addition of one of more RIMS, for example in the west of Ireland.
- Continuity performance was observed to be sensitive to the elevation mask angle set in the ship's receiver. Higher mask angles (e.g. 15°) protect against multipath effects, but can exclude satellites which may be important to the continuity of the solution and which would be included with lower mask angles (e.g. 5°). A trade-off is necessary between improved satellite geometry and increased measurement errors, arising from variations in the elevation mask. It would appear to be important for receiver manufacturers to adjust the pre-setting of the elevation mask angle, within the ongoing development of the IEC test specification for MSR type approval.

Regarding a possible future EGNOS V3 maritime service, MarRINav has made a number of recommendations for potential changes. The EGNOS V3 as designed for aviation is not optimised to provide the information needed to satisfy user-level maritime requirements. EGNOS inflates position error overbounds conservatively for aviation, whereas maritime integrity may be better accomplished using best-estimate ("fault free") error models. It is necessary to determine a nominal vessel multi-path model, and the associated probability with which instantaneous measurements exceed this model (fault probability). This issue could be addressed by changing the system requirements for the 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, this change would also support other non-aviation sectors, each having its own optimised receiver design to use the new SBAS information in the most appropriate way.

MarRINav also found that an innovative Maritime RAIM (M-RAIM) – described in full technical detail within the project reports - is a method that shows considerable promise as a candidate form of RAIM for inclusion in the maritime receiver. It is recommended that 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 marine locations outside SBAS coverage).

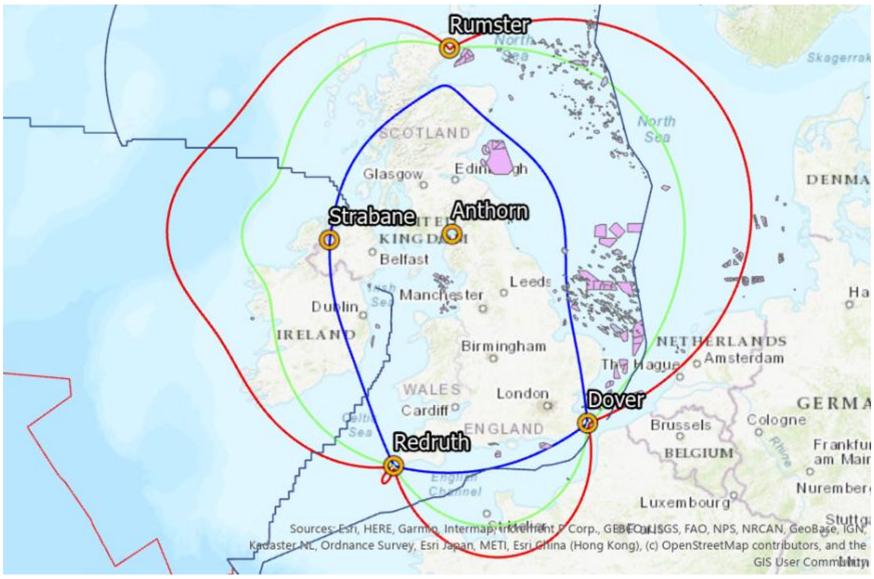
4 'MarRINav' conceptual architecture solution

Candidate technologies have been described that could contribute to a conceptual PNT architecture for Resilience & Integrity of the maritime Critical National Infrastructure of the UK, but with a view to achieving wider cross sector capabilities. The required coverage and performance demands the development of a hybrid system-of-systems, recommended to include:

- **E**nhanced **Lo**ng **Ra**nge **N**avigation - eLoran
- Ranging mode of the VHF Data Exchange System - VDES R-Mode
- Radar Absolute Positioning
- LEO Satellite Timing and Location (STL), subject to performance confirmation
- LOCATA at ports
- Onboard systems, to integrate traditional and/or inertial Dead Reckoning.

The hybrid system-of-systems PNT solution adopts the principle of primarily using the wide area eLoran system for maximum overall geographic coverage, then supplementing this with regional VDES R-Mode and/or radar absolute positioning to fill capability gaps in the wide area coverage. Where more than one separate PNT solution is available, they can be combined in the receiver (MSR) with Dead Reckoning, as an integrated navigation solution. 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 through 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.

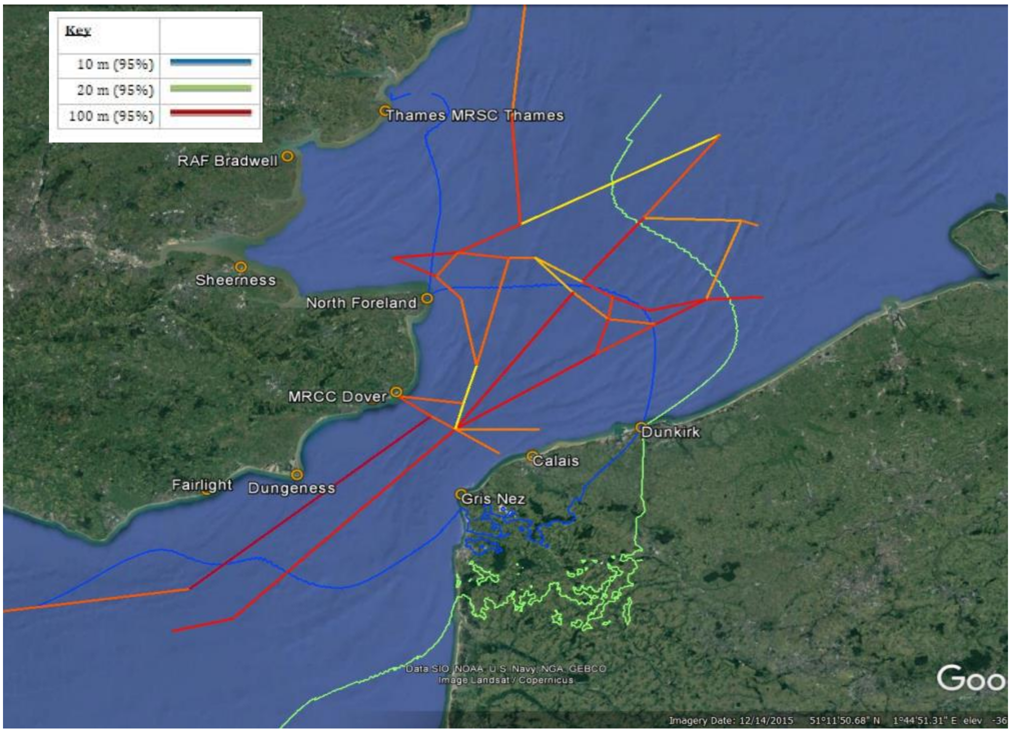
5 Geographic coverage for maritime resilient PNT



Accuracy coverage contours of UK based eLoran. Blue = 10 m, Green = 20 m, Red = 30 m.

The UK eLoran coverage provides better than 10m (95%) accuracy at 9 out of the 10 most major UK ports and many coastal areas achieve better than 20m (95%), as shown in the figure above. However, the port and straits of Dover, together with the north-eastern approaches to the Channel, are less adequately covered. It was noted that coverage could be extended into these more challenging areas if eLoran transmissions were to be resumed from the Sylt transmitter station in Germany. 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 around the Dover Straits. This would clearly be 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.

Analysis of the potential deployment of UK-only VDES R-Mode stations alone has found that UK-only R-Mode is insufficient to fill the gap in positioning capability. 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 were not considered in this stage of the project. The inclusion of just three VDES R-Mode stations in France, along with the UK VDES R-Mode baseline, was 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 Traffic Separation Scheme (TSS) and its approaches to the north-east of Dover, arguably one of the highest risk maritime areas in the world. The capability gap in this area 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), as seen in the figure below.



Accuracy contours for Integrated VDES R-Mode & UK-only eLoran. Blue = 10 m, Green = 20 m.

6 Cost benefit analysis (CBA)

The CBA considered the central economic case of maritime transportation and assumed that one 5-day wide area outage of GNSS (Global Navigation Satellite System) will take place within the next 10 years, with certainty. The analysis focuses on a scenario with container ships only. 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 benefits are the loss avoided due to a GPS outage, whilst the costs are those of implementing and maintaining the system-of-systems PNT architecture.

As 69% of the total goods economic value transits through containers in the UK, the overall value attributable to containers amounts to £601m. Maritime transportation would be hit by a maximum loss of efficiency during the GPS outage. 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 value loss with MarRINav technologies available to provide resilient PNT during the GNSS outage is less, due to improved efficiencies. Without the MarRINav solution, the total economic loss is **£601m** whereas, with the MarRINav system-of-systems in place, the total loss is reduced to **£180m**. Under our assumptions, the total economic value saved is **£421m.**

The global number of container vessels at the end of 2018 was approximately 5,200. Costs were split into two categories namely ashore infrastructure costs and ship-owner costs. The present value of costs for onshore technologies is **£80m** over 10 years, as tabled below.

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

Costs of ashore infrastructures per unit

The onboard technologies alongside the capital and operational expenditures are further tabled below. Overall, the investment cost per ship is equal to **£23,000**. Therefore, the costs to ship-owners is only an upfront investment. In total, the cost to ship-owners 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

Costs of on-board equipment per ship

As shown in the table below, 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 ship-owners	120
Net Present Value	**+221**
Benefit-cost ratio	**2.2**

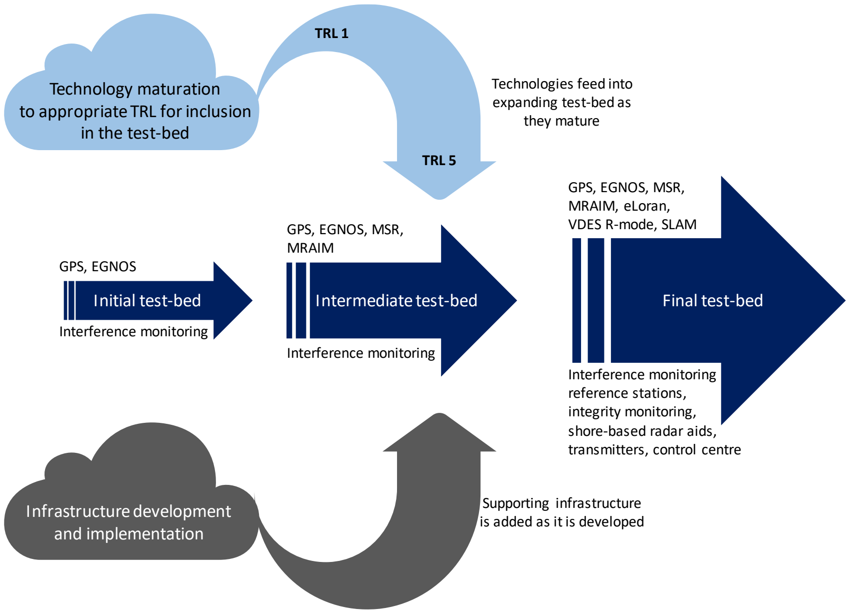
Summary of benefits and costs

7 Conclusion and recommendations

Further research and development in future phases of the MarRINav project would seek to prove the concept of the PNT solution architecture and the effectiveness of M-RAIM in conjunction with a possible future maritime user-level integrity service based on EGNOS v3.

An Outline Development Plan has indicated how to implement a test-bed demonstrator to prove the concept of the hybrid system-of-systems solution at a local scale for a variety of users (not confined to maritime). Outputs from the test-bed demonstrator would support design and implementation of a resilient PNT architecture for CNI at UK national scale. The Outline Development Plan identifies proof-of-concept activities over at least two years, based on the implementation of a **physical** system-of-systems into a **test-bed** demonstrator. This would be supported by a modelling & **simulation test-bed** to provide insights for its physical realisation.

The philosophy of the test-bed development process is to build incremental development of each system's technological maturity (i.e. increasing their Technology Readiness Levels) before integration as a system-of-systems. This development concept is illustrated in the figure below.



Test-bed demonstrator growth concept

With 95% of all UK imports arriving by sea, it is hard to overstate the importance of maritime shipping's societal impact and the benefits of the MarRINav solution to the UK national interests. Movement of goods in an efficient manner is vital to the economic and social welfare of those living in the UK. The concluding roadmap of the project has supported 3 key 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

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