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MarRINav
MARITIME RESILIENCE AND INTEGRITY OF NAVIGATION

D7 Outline Development Plan

28th February 2020

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MarRINav – Maritime Resilience and Integrity in Navigation
Work Package 4 Outline Development Plan

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Summary

MarRINav Work Package 4 (WP4) has elsewhere described [1] a conceptual architecture to provide resilient Positioning Navigation and Timing (PNT) capability for UK maritime critical national infrastructure (CNI). The concept of the resilient PNT hybrid system-of-systems solution is to supplement the ubiquitous satellite-navigation solution with a terrestrial infrastructure of radio navigation transmitters (and supporting communications technologies), together with elements for their control, data processing, integrity monitoring and differential correction. The infrastructure will provide radio navigation signals and information primarily to ships and ports, but also precise timing and navigation capability to land-based users in diverse sectors throughout the UK.

Maritime users must be suitably equipped to derive hybrid navigation solutions across the constituent technologies. Vessels fitted with a multi system receiver (MSR) conforming to the associated International Maritime Organisation (IMO) performance standard [2] will gain the benefit of accuracy, integrity, availability and continuity of navigation, even in situations when GNSS is degraded or denied by natural interference or jamming. The technical considerations required for a MSR to utilise the MarRINav solution effectively have also been described elsewhere [3] in WP4.

The component positioning technologies of the concept are currently at differing levels of technical maturity, as indicated by their Technology Readiness Level (TRL) as explained previously [4] in WP 3. Hence, further research and development (R&D) is required to grow the maturity of these individual systems and to demonstrate their combination as a hybrid PNT system-of systems solution for UK maritime CNI.

This report, deliverable D7 of MarRINav, sets out an 'Outline Development Plan' to progress the next technical steps of the PNT solution as a test-bed demonstrator. This Outline Development Plan will form the core of the proposal for a future Phase 2 of the MarRINav project. The aim of the test-bed demonstrator is 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 Outline Development Plan forms a near-term part of the overall MarRINav

roadmap [5] that defines the steps to the delivery of resilient high-integrity PNT within UK maritime CNI over the timeframe to 2030 and beyond.

The five stages of the Outline Development Plan are:

- **Planning**: confirmation of objectives, elaboration of a detailed plan, specification of requirements and location assessment for the test-bed demonstrator.
- **Design and Development**: maturation of technologies within the system-of-systems solution, and modular design of the systems-of-systems following systems engineering principles.
- **Software Test-Bed**: models of technologies and prediction of hybrid service coverage areas to support physical demonstration and validation from real-world results.
- **Physical Test-Bed**: implementation of bare-bones demonstrator for proof-of-concept of the hybrid PNT solution.
- **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.

It is recommended that this Outline Development Plan be used as the basis of a proposal to the ESA NAVISP Programme Element 3 (National Interest), as a Phase 2 of the MarRINav project. Phase 2 is recommended to run for at least two years, from mid-2020 to mid-2022 and beyond, with a scope to be accommodated within the available budget of NAVISP Element 3 in accordance with the ESA Council of Ministers decisions taken in November 2019.

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Glossary

ASF	Additional Secondary Factor
CBA	Cost Benefit Analysis
CNI	Critical National Infrastructure
D	Deliverable
DR	Dead Reckoning
EEZ	Exclusive economic Zone
EGNOS	European Geostationary Overlay Service
ePD	e-navigation Prototype Display
eRacon	Enhanced Radar Beacon
ESA	European Space Agency
GAGT	GLA Augmented GNSS Toolset
GLA	General Lighthouse Authorities
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMO	International Maritime Organisation
IP	Intellectual Property
MarRINav	Maritime Resilience and Integrity of Navigation
MRAIM	Maritime Receiver Autonomous Integrity Monitoring
MSR	Multi-System Receiver
NAVISP	Navigation Innovation and Support Programme
NPL	National Physical Laboratory
ODN	Operational Data Network
PNT	Position, Navigation and Timing
QT	Quantum Technology
R&D	Research and Development
RaDR	Radar Dead Reckoning
RAIM	Receiver Autonomous Integrity Monitoring
R-mode	Ranging Mode
SDR	Software Defined Radio
SLAM	Simultaneous Location And Mapping
STL	Space-based Timing and Location
TRL	Technology Readiness Level
TSS	Traffic Separation Scheme
TWLFTT	Two Way Low Frequency Time Transfer
TWSTFT	Two Way Satellite Time and Frequency Transfer
UK	United Kingdom
V2	Version 2
VDES	VHR Data Exchange System
VHF	Very High Frequency
WP	Work Package

1 Introduction

1.1 MarRINav overview

The MarRINav project was originally planned in three phases as shown in

Figure 1, each of 12 months duration, subject to further ESA approval and funding under NAVISP Element 3, as illustrated in the diagram below. From the outset, it was recognised that Phases 2 and 3 may be combined over 24 months.

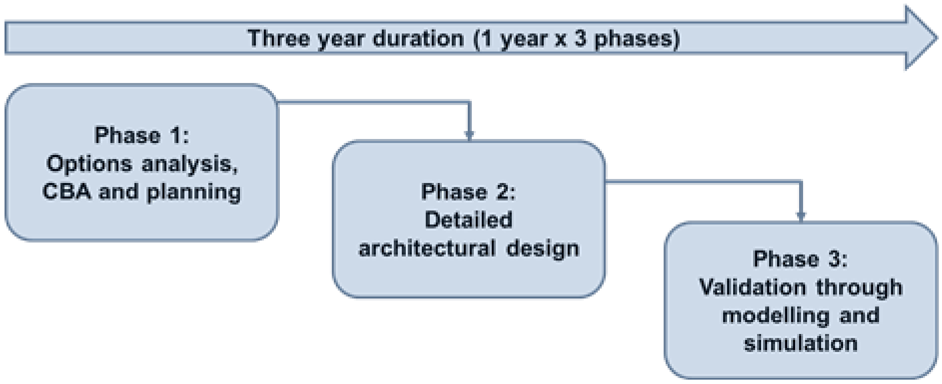

Figure 1: Original MarRINav phasing

Phase 2 was intended to build on this conceptual solution, adding design detail in order to create an architectural framework. Phase 3 was aimed to validate the architectural framework through performance modelling and simulation, culminating in a detailed roadmap for the implementation of the infrastructure architecture.

The Phase 1 work has identified further specific areas of research and development (R&D) needed to reduce technical risk and progress the technology immaturity to a higher Technology Readiness Level (TRL). This would be best achieved through a modification of the planned future phases into a new combined Phase 2 to develop a test-bed demonstrator, as shown in

Figure 2. This new Phase 2, as illustrated below, is expected to have a duration of at least 24 months and conduct research on key immature components of the system-of-systems solution as well as the overall system-of-systems itself. The test-bed demonstrator would address specific technical challenges as practical solutions realised at a local but expandable level. The test-bed demonstrator would be supported by extensive software modelling and simulation.

The new, two-phase approach to MarRINav has inherent risk mitigation measures built into the gradual and evolutionary parallel development of hardware and software demonstrators:

- The approach is modular, enabling incremental growth of the demonstrator rather than basing this on a single build as in the previous approach.
- Technology risk is managed by the gradual development of the constituent systems of the overall systems-of-systems separately until they have reached the appropriate TRL with a high level of confidence before they are built into the demonstrator.

- Parallel development of software and hardware demonstrators will enable cross-fertilisation of lessons learnt, will identify any actions needed, modify hardware and/or software designs as early as possible in the development process and will facilitate timely validation and verification.

Together, the test-bed demonstrator and software models will raise confidence in and provide proof-of-concept of the MarRINav conceptual architecture developed in Phase 1. This will enable progression to a future overall detailed architectural design for the system-of-systems implementation at UK national scale.

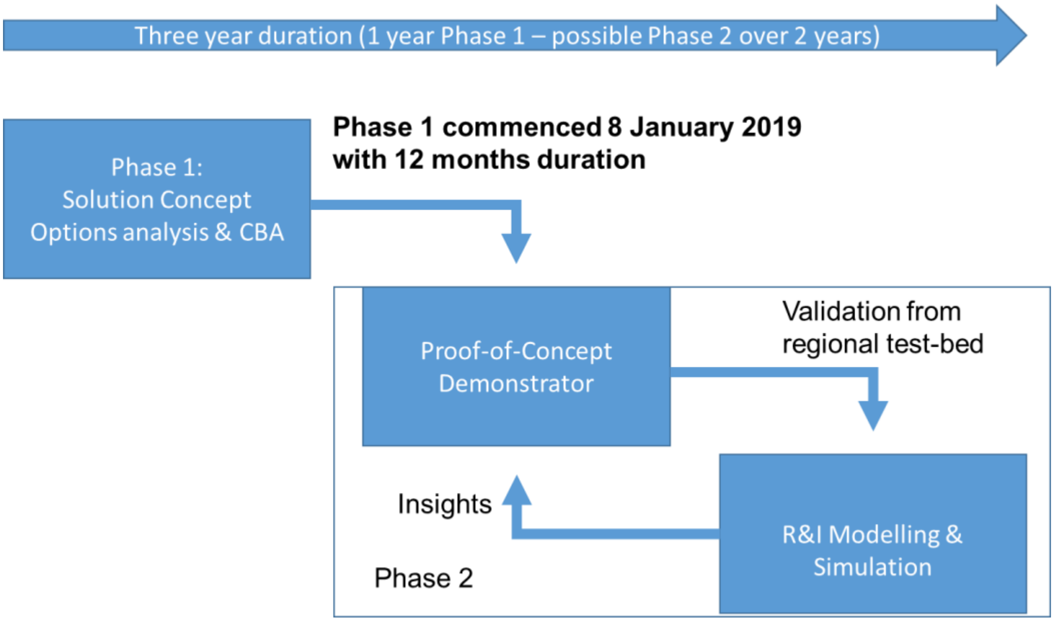

Figure 2: Revised MarRINav phase 2

1.2 Conceptual architecture

Figure 3 illustrates the conceptual shore-based architecture required to provide resilient position, navigation and timing (PNT) for UK maritime critical national infrastructure (CNI). This shore-based architecture, which will form the basis of this Outline Development Plan, comprises the land-based functions of the resilient PNT solution, viz radionavigation transmitters, differential reference stations, integrity monitoring stations, a universal time coordinated (UTC) time source and a control centre.

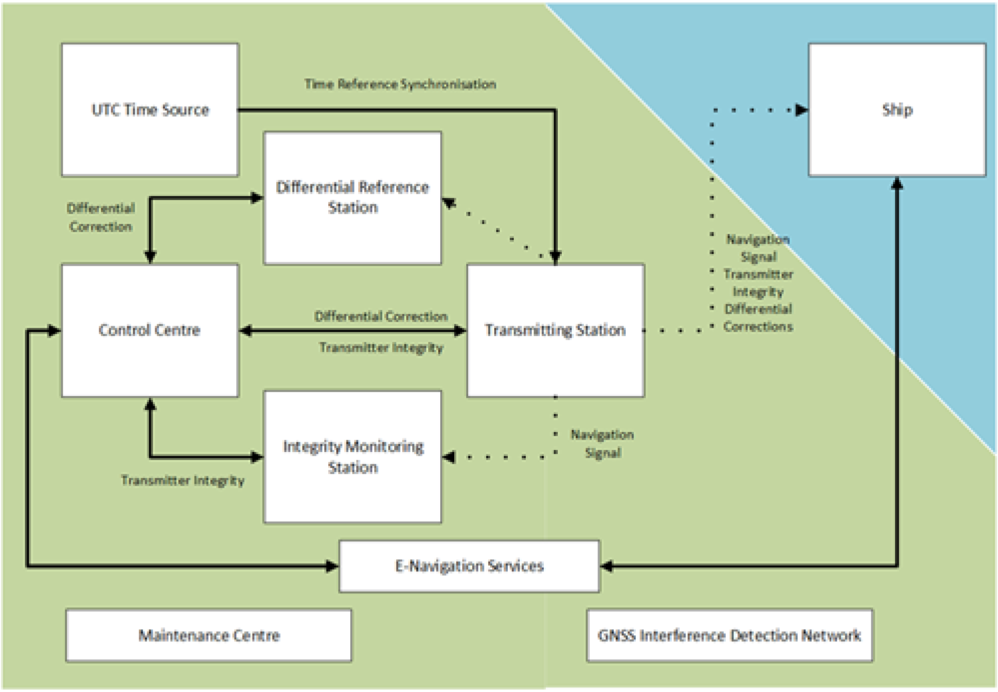

Figure 3: Conceptual architecture

In the test-bed demonstrator, the land-based components of the resilient PNT solution will be supplemented by on-board functions, including the multi-system receiver (MSR) including maritime receiver autonomous integrity monitoring (MRAIM), radar and processing for radar-based positioning, as well as the usual shipborne systems. Full details of the conceptual architecture are provided in MarRINav deliverable D5 [1].

1.3 Integration into a system-of-systems

The test-bed demonstrator will comprise a prototype system-of systems integrating GNSS including GPS, Galileo and the European Geostationary Overlay Service (EGNOS), eLoran and Very High Frequency (VHF) Data Exchange System (VDES) ranging mode (R-mode) technologies with shore-based augmentation for ship's radar. These will support the ship's MSR navigation solution, in combination with the ship's radar image processing, the ship's Dead Reckoning (DR) – speed log & gyrocompass - and receiver autonomous integrity monitoring (RAIM). If available within the timeframe of the Demonstrator, the contribution of a Quantum Technology (QT) clock on-board the ship will also be evaluated.

As Locata is a well-established system with proven capabilities and will need bespoke implementation on a port-by-port basis, it will not be included in the test-bed demonstrator. Another of the candidate technologies, space-based timing and location (STL), is of low maturity and outside of the control of MarRINav so it will also not be included in the test-bed demonstrator but will be evaluated separately.

1.4 Test-beds

The test-bed demonstrator includes the prototyping, integration, demonstration and evaluation of the concept shown in
Figure **3**. Its principal objective is to construct a physical realisation of the system-of-systems albeit covering a limited geography at a suitable location selected to be representative of a sufficiently challenging navigation environment to enable proof-of-concept.

In parallel, a software test-bed will be developed containing models of the conceptual architecture that are applicable across the UK. The software test-bed will be used to inform the development of the physical test-bed. In turn, the outputs of the physical test-bed will be used to validate the software test-bed to increase confidence in its use as one of the main tools used in the detailed design of the UK-wide solution.

Together both demonstrators will address key technical risks and inform future detailed design in support of policy decisions for the solution to be implemented at national scale.

1.5 Development concept

The development concept is to raise the component technologies comprising the system-of-systems to the appropriate TRL level and to integrate those technologies to provide a test-bed demonstration at TRL 6. TRL levels are explained in the overview illustrated in
Figure **4**.

Table **1** provides indicative TRL levels for the component technologies of the MarRINav system-of-systems to indicate where additional development effort is needed to raise these individual components to the target level of TRL 5 or TRL 6 to enable them to be demonstrated in the system-of-systems at TRL 6.

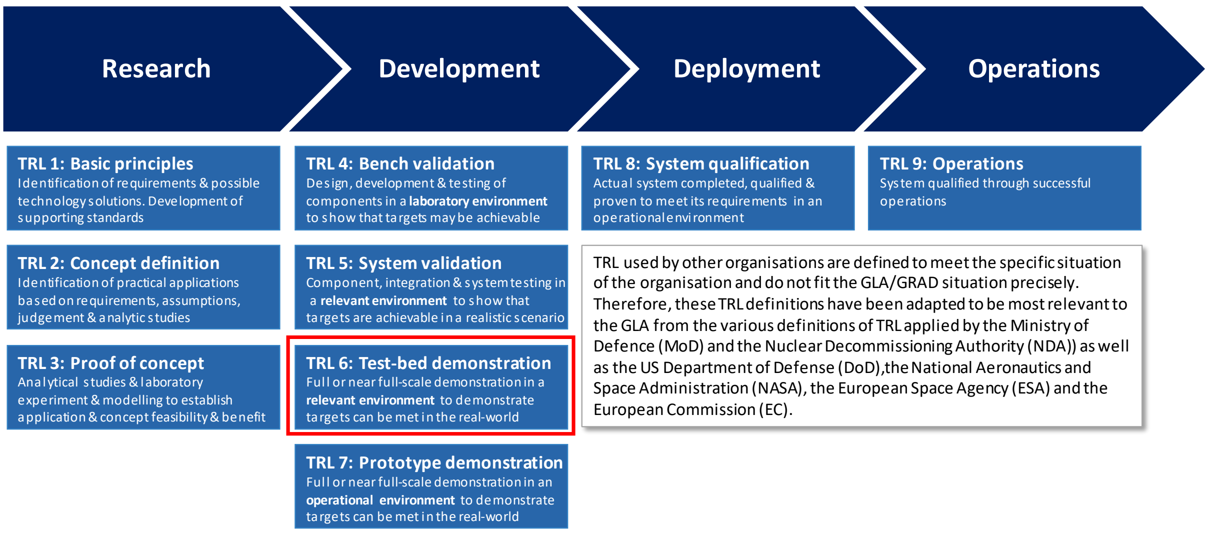

Figure 4: Overview of TRL levels

Technology	Rationale	TRL
eLoran	Basic eLoran, together with ASF corrections and dLoran, has been shown to be capable of delivering PNT to the level needed to meet maritime requirements to port approach level. The feasibility of two-way time transfer between eLoran stations has been proven However, the feasibility of transmitting eLoran from TV masts as in the MarRINav concept is not validated and the levels of timing precision potentially needed to support time synchronisation to UTC in the resilient conceptual architecture has not been demonstrated	7 3
Radar Absolute Positioning	There are 2 main methods proposed here: 1. The feasibility of Simultaneous Location and Mapping (SLAM) has been demonstrated by modelling in a laboratory environment. Further work is needed to establish feasibility in relevant and operational physical environments 2. Use of enhanced radar transponder beacons (eRacons) has been demonstrated in a relevant environment as a standalone system	3 5
Satelles (STL)	The concept of using STL as a source of position information has been established but little is known about the practical feasibility and performance of this approach	2
VDES R-mode	Proof-of-concept of VDES R-mode has been established using modelling and simulation and limited demonstration using physical systems. The mechanisms for time synchronisation for VDES R-Mode and the potential for using VDES- R-mode for time synchronisation are at concept stage	4 2
Locata™	Locata™ is established as an operational system in some ports	9
MRAIM	The MRAIM concept has been investigated mathematically and theoretical algorithms have been developed. These algorithms have not been implemented or tested	2
MSR	The MSR concept is well developed and understood but has not been fully proven nor implemented in hardware and software	2

Table 1: Candidate technology TRL levels

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 5, which shows the test-bed demonstrator growing as the component technologies are matured and the supporting infrastructure is developed and included. Note this figure currently only illustrates the concept and the exact development path for the test-bed demonstrator will be elaborated during the early part of MarRINav Phase 2.

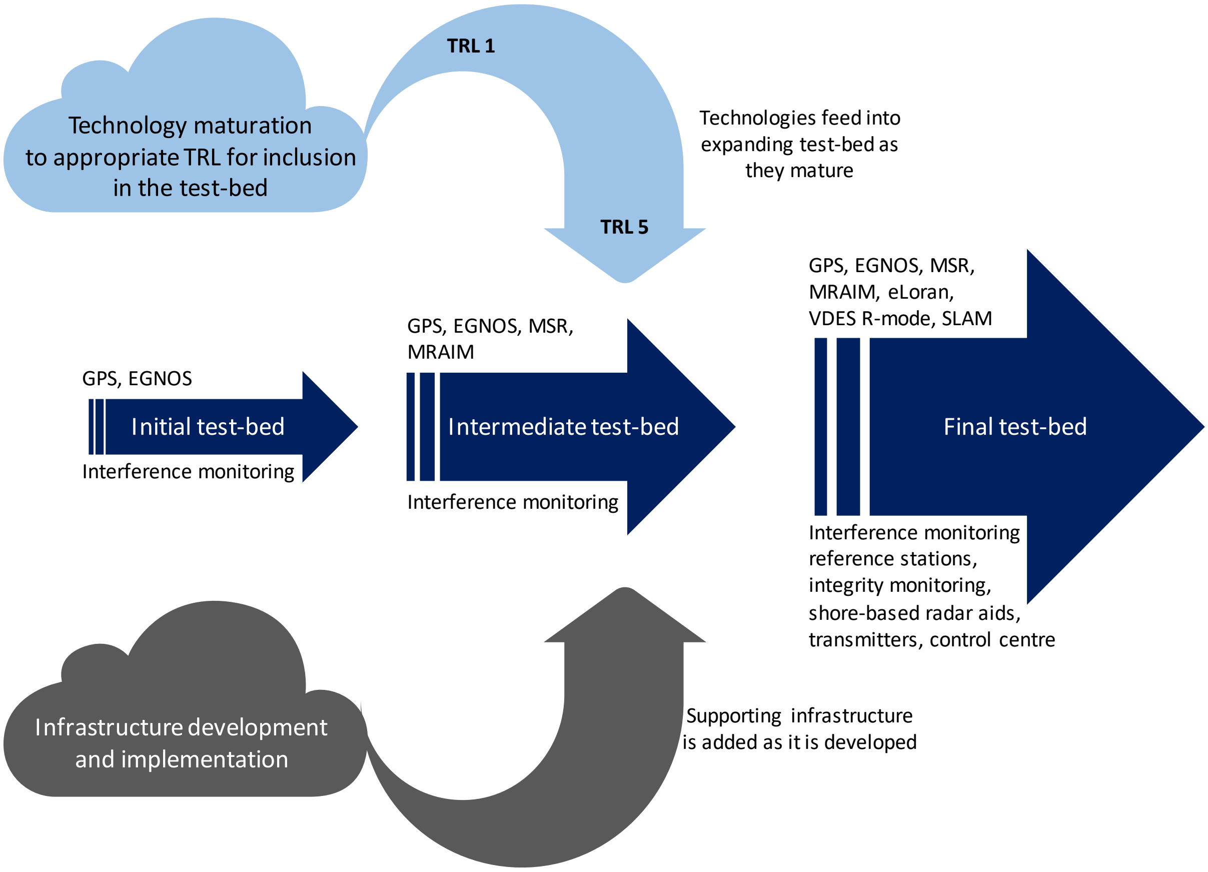

Figure 5: Test-bed demonstrator growth concept

The MSR is a critical component of the MarRINav test-bed demonstrator, as illustrated in the table and figures above. It is understood that there are a number of ongoing projects within Europe and elsewhere aimed at developing, testing and validating the MSR. For this reason, MarRINav does not aim to develop the MSR itself, other than the M-RAIM algorithms that will likely be included in the MSR. Instead, MarRINav intends to coordinate closely with the current MSR projects to contribute to MSR requirements, influence design and provide guidance to standardisation. If it becomes apparent that a suitable MSR will not be available to the appropriate TRL through other projects, MarRINav will review its approach to the MSR.

1.6 Development process

The end-to-end development process is illustrated

Figure 6 below.

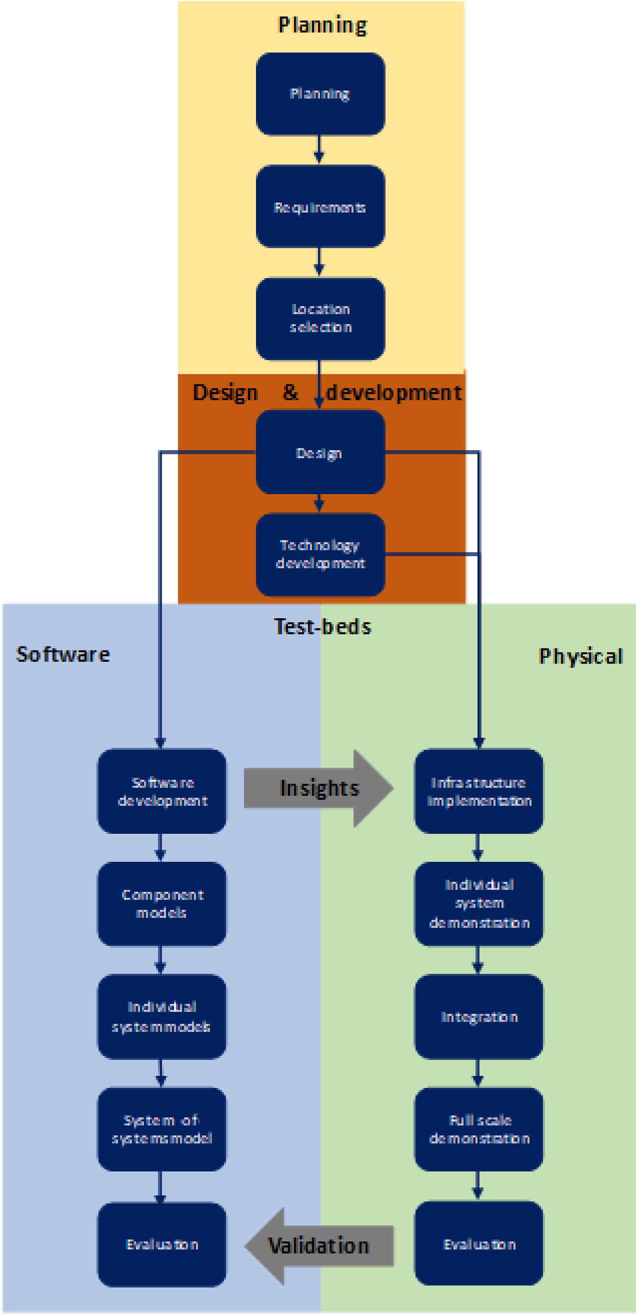

Figure 6: Development process

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 requirements will include functional and non-functional elements, and the test and evaluation plan, including assessment of performance. 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 illustrated in
3. Figure **3**. The design will also specify the functions to be performed in the common building blocks, such as the control centre. Data flows will also be defined. This stage of the work will also identify the development actions needed to bring each of the technologies to a sufficiently mature TRL for them to be incorporated in the physical test-bed. A programme of work will then be defined and executed to develop these technologies to the required level.

4. 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. Initially the software test-bed will replicate the design for the physical test-bed but will be expandable to give full UK coverage. The software test-bed will be developed using agile techniques to enable early results to be generated to:

    a. inform the development of the physical test-bed;
    b. feedback into the design when there is sufficient confidence in the results.

    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.

5. 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. This will then be used to investigate proof-of-concept at the test-bed location. Performance and other system parameters will be used to refine and validate the software test-bed to enable its expansion into a full design tool.

2 Outline development plan

2.1 Planning stage

The overview of the planning stage for the test-bed demonstrator is illustrated in the following figure. This stage comprises four main steps, which are described in more detail below, as well as a feed-back loop to enable location specifics to be included in the detailed Development Plan.

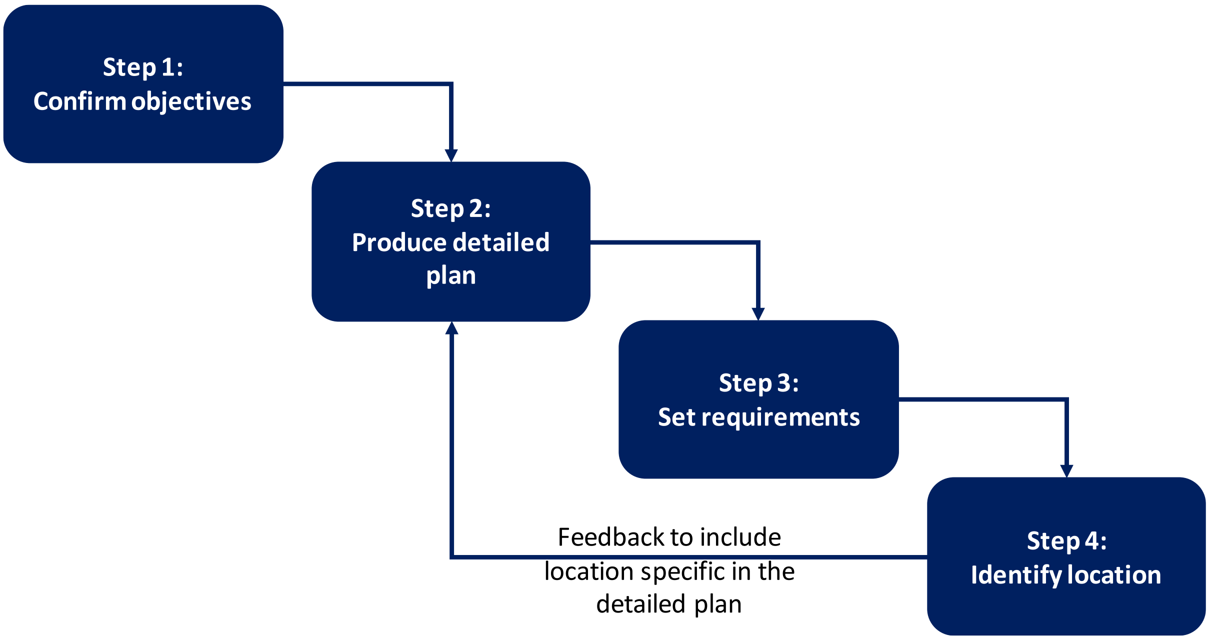

Figure 7: Overview of the planning stage

2.1.1 Confirm objectives

The overall objective of the Development Plan is to design, develop, implement and apply physical and software-based test-bed demonstrators to validate the feasibility of the MarRINav conceptual architecture for the system-of-systems to provide resilient and high integrity PNT in the maritime sector.

The first part of the planning stage of the development will be to set the specific objectives for the test-bed demonstrators. These objectives will be specific, measurable, achievable, relevant and time-bound (SMART). The objectives will be likely to include:

- confirming the feasibility that the low TRL technologies can be developed to make their own contributions in the system-of-systems and develop those technologies to sufficient maturity to be trialled in the test-bed demonstrator;
- increasing confidence that the conceptual architecture can meet the navigation performance requirements for resilient PNT;
- identifying any shortcomings, e.g. low performance in certain critical geographical areas, to enable further required research and development (R&D) to be planned;

- identifying any major differences in cost to those used in the initial cost-benefit analysis (CBA) in Phase 1 of MarRINav;
- identifying and mitigating major development, implementation and operational risks for the conceptual architecture.

2.1.2 Produce detailed plan

Based on the objectives, a detailed plan will be developed using this Outline Development Plan as the starting point. The detailed plan is critical to confirm estimated costs and timescales and to identify skill and resource requirements.

2.1.3 Set requirements

Requirements for the test-bed demonstrator will be based on the user and system requirements for the PNT system-of-systems captured in work package WP 1 of MarRINav and described in Deliverable D1 [6]. However, these will be stripped down to the bare essentials for a functioning PNT test-bed, by omitting, mainly non-functional, aspects that are only necessary for the robustness, longevity and ease of maintenance of the final operational solution. It will also include only the minimal number of elements needed for proof-of-concept of the PNT functions in the selected regional location of the test-bed; in particular no more than one or two additional eLoran transmitter(s), beyond the existing transmitter at Anthorn, and no more than three VDES R-Mode stations are expected to be required.

2.1.4 Identify location

The test-bed location must be selected, accounting for a number of factors, which include:

- Vessels in coastal, port approach and port voyage phases, associated with a major port with adjacent high risk navigational areas. Possible examples include the ports of Dover, Felixstowe, Liverpool and Southampton.
- Adequate eLoran coverage offered by reasonable geometry of the two sightlines to the transmitters - Anthorn and one or two additional transmitter(s) at an existing TV mast - from receivers in the test-bed area.
- Potential for good VDES R-mode coverage within at least a localised area of the test-bed, affording line-of-sight transmissions to the vessel and sites for R-Mode stations with adequate geometry of sightlines from the receiver to the transmitters.
- Participation of a small number of cooperative vessels (e.g. THV Galatea) with accommodation for trials personnel, observers, prototype MSR, PNT displays and data recorders.
- Ease of access for trials personnel, equipment and VIP observers at demonstrations.
- Potential for future test-bed extension to a wider set of e-Navigation prototype services.

As needed, the specifics of the location will be fed back into the detailed plan.

2.2 Design and development stage

The design and development stage comprises two main steps, as illustrated in

Figure 8.

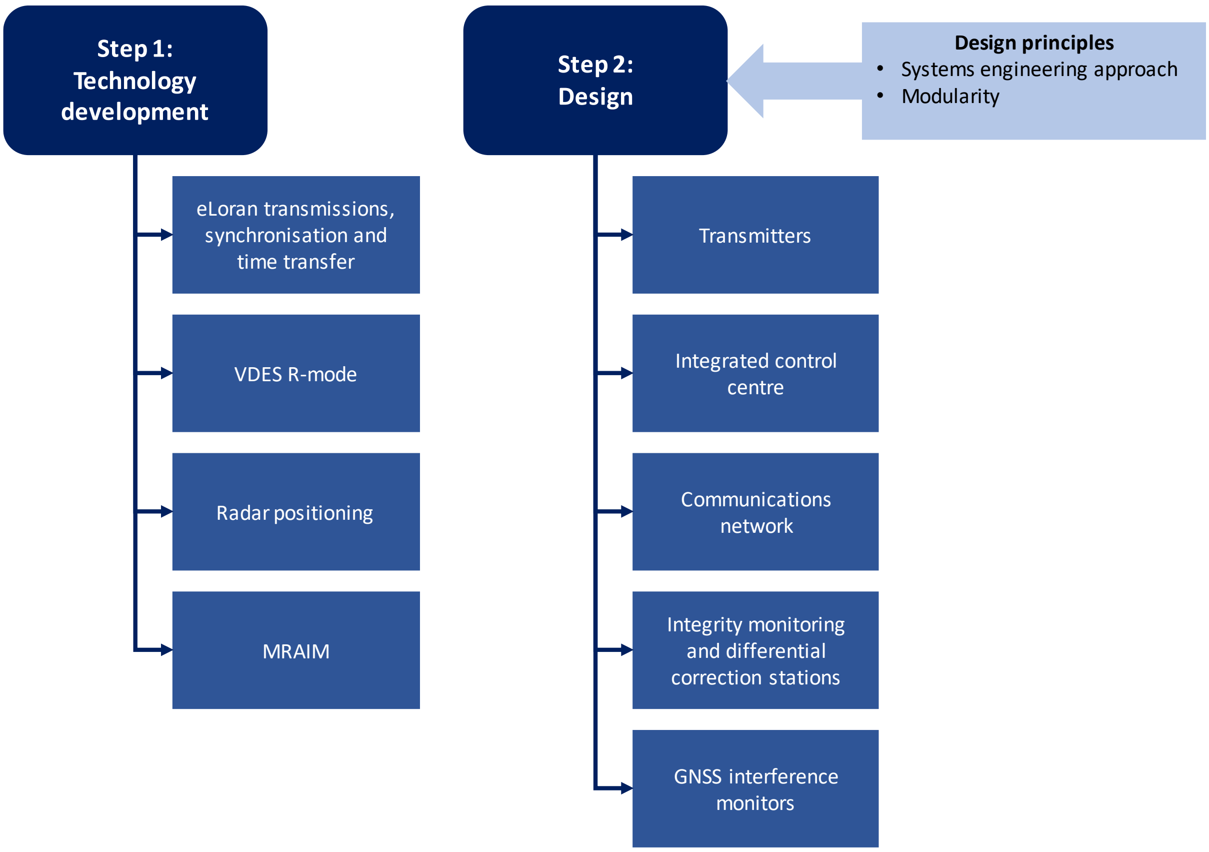

Figure 8: Elements of design and development stage

These steps are:

- technology development
- design, underpinned by a systems engineering approach and the principle of modularity to enable gradual evolution of the test-bed demonstrator in terms of functionality, scope of systems included and geographic coverage.

2.2.1 Technology development

Several constituent technologies supporting the conceptual architecture must be matured through further research and development before their deployment within the test-bed demonstrator and test-bed. These are:

- eLoran transmitting station(s) and UTC time transfer
- VDES R-Mode transmitting stations and synchronisation
- radar positioning
- Maritime RAIM (MRAIM).

2.2.1.1 eLoran Transmissions, Synchronisation and Time Transfer

eLoran is per se a relatively mature technology, including its methods of measuring and correcting for Additional Secondary Factors (ASFs) (correction for spatial variation of eLoran signal propagation delays) and the techniques of Differential Loran (correction for temporal variation in eLoran signal propagation delays).

The precise transfer of UTC time from NPL (or a future UK National Timing Centre operated by NPL) to one (or more) eLoran transmitter(s), using either Dark Fibre or Two Way Satellite Time and Frequency Transfer (TWSTFT) is a relatively mature technique. Once a single eLoran transmitter has been synchronised to UTC, the method of transferring precise time to other eLoran transmitters is also mature by Two Way Low Frequency Time Transfer (TWLFTT) to synchronise eLoran transmissions with each other (q.v. Annex C.4).
However, there are two associated technology areas which are less mature and require further development prior to full proof-of-concept demonstration. These are:

- The use of existing TV mast infrastructure to act as the eLoran signal antenna, for lower-power transmissions (as described in Annex B.4.2 of D5 [1]).
- The use of the de-centralised technique for TWLFTT for synchronisation of eLoran transmitters (as described in Annex C.4.1 of D5 [1]).

2.2.1.2 VDES R-mode

Several methods of VDES R-Mode are under consideration, as explained in Annex E of D5 [1]. The basic method of one-way ranging, accepting that position solution ambiguity can be resolved by proximity to the last known GNSS position, requires three VDES R-Mode transmissions to be received. These must be synchronised with each other, and also to UTC (or the offset from UTC be made available to the receiver) if the R-Mode pseudorange measurements are to be used in a tightly-coupled PNT solution. Crucial aims in the technology maturation of VDES R-Mode are to prove the concepts of:

- synchronisation (ideally totally independent of GNSS), potentially using eLoran for the transfer of precise time (to the order of 10 nanoseconds) to VDES R-Mode transmitter stations (as described in Annex D.3.2 of D5 [1]). A number of synchronisation techniques have been proposed (summarised in Annex D.4 of D5 [1]).
- positioning capability in the real environment with ambient VHF noise and varying signal reception with range from transmitters. A two-way ranging technique could

also be explored further, though noting that this would be limited to occasional use in order not to compromise the VDES communications functions (q.v. Annex D.3.1.1 of D5 [1]).

2.2.1.3 Radar positioning

The technique of Radar Dead Reckoning (RaDR) integrated with Simultaneous Location And Mapping (SLAM), as described in Section 4.2.5 of D4 [4], is relatively immature and needs to be evaluated against a variety of coastal conditions with variations of natural features and targets within the built environment. This requires the collection and analysis of radar data sets, which should also include shore-based infrastructure of passive radar reflectors (e.g. radar 'bar codes' on lighthouses) and/or active Enhanced Radar Beacons (eRacons) to determine the effectiveness of such augmentation. A real-time radar positioning capability would be explored to investigate the integration of the integrated technique of RaDR with radar image SLAM.

2.2.1.4 Maritime RAIM (MRAIM)

The MRAIM technique has been defined in mathematical detail by the GLA in D3b [7], as GLA background intellectual property (IP) but openly published in the public domain to encourage its further development. The GLA description of MRAIM has been successfully peer reviewed by Stanford University. A model of MRAIM needs to be developed and tested against recorded GNSS data sets in the maritime environment to move it up the TRL scale. The development of MRAIM would cover a real-time version of MRAIM and its performance in representative operating environments with realistic levels of multipath causing simultaneous faults on signal reception from multiple satellites.

2.2.2 Design

As the technology components mature to a reasonable TRL then the designs of the software test-bed and physical test-beds can be evolved. These will be based on the conceptual architecture of

Figure 3, incorporating prototypes of the maturing technologies described above, together with the following elements, all linked by a preliminary operational data network (ODN) capable of supporting the flow of PNT-related information:

- transmitters (eLoran and VDES);
- bare-bones integrated control centre;
- communications network (ODN and data flows internal to architectural elements);
- common (as far as possible) integrity monitoring and differential correction; reference stations;
- GNSS interference monitors.

2.2.2.1 Systems engineering

Using a systems engineering methodology, the test-bed demonstrator design should respond to the requirements and location constraints identified in the planning stage (section 2.1). Ideally, the designs should be developed utilising systems engineering tools (such as CRADLE and SysML/UML), addressing two key objectives:

- Facilitation of systems design, implementation and testing by a multi-disciplinary engineering team dispersed across industry, academia and public sector collaborators
- Potential re-use as the starting point for a future formal design of the UK solution at national scale.

2.2.2.2 Modularity for stepwise design

The test-bed demonstrator design will be modular to enable ease of integration and the removal or inclusion of components to support investigation of a range of system-of-systems configurations. In particular, the designs should provide a stepwise completion of the hybrid technology:

- Fundamental GPS/Galileo multi-constellation PNT with equivalent of EGNOS version 2 (V2) 2 'maritime A.1046 service' capability for integrity at system level;
- Integration of GNSS with eLoran for resilience of maritime positioning and multi-sector time distribution;
- Inclusion of MRAIM for GNSS integrity at user level;
- Integration of VDES R-Mode within the system-of-systems;
- Integration of RaDR SLAM positioning within the system-of-system.

2.3 Software test-bed

The GLA have an existing suite of software models that can be used to evaluate the performance of individual maritime PNT technologies and to predict the service coverage area of these for a given required performance level. Models of GNSS, eLoran and their integration are validated against extensive real-world data. Models of maritime EGNOS, MRAIM, VDES R-Mode and radar positioning are in various differing states of validation. The models will be further extended and validated against physical test-bed measurement data and used to estimate performance, evaluate service coverage areas, validate assumptions and refine the architectural concept, ultimately through to the proof-of-concept demonstration.

2.3.1 GNSS, eLoran and VDES R-Mode Integration

The core version of the software test-bed will combine GNSS with eLoran and VDES R-Mode to deliver a hybrid position solution.

A GLA model of combined hybrid performance of a system-of-systems solution is available which can represent both loosely-coupled and tightly-coupled integration of position/velocity/time (PVT) measurements and pseudorange measurements respectively within the MSR. It may be possible to extend the models to evaluate the hold-over performance of the hybrid solution in periods of GNSS non-availability, when integrated with traditional DR (speed log and gyrocompass) and with various grades of inertial DR. Loosely coupled integration of the RaDR SLAM technique will also be considered.

2.3.2 Trade-off Analysis

The system-of-systems models will support trade-off analysis of transmitter powers, locations and geometries across the technology mix, the effects of differential position corrections and their spatial decorrelation as a function of the receiver's distance from reference stations.

2.3.3 MRAIM and EGNOS

A model of MRAIM will be developed from its mathematical description and used to simulate its performance across a range of maritime multipath environments. A limited number of example data sets of GNSS measurements could be gathered from ship trials to conduct an initial assessment of MRAIM capabilities. A separate ESA NAVISP project has collected more extensive GNSS data sets on ships (representative of various multipath conditions) and if some of these could be made available by arrangement with ESA then a wider evaluation of MRAIM would be possible.

It is recognised that modelling maritime EGNOS performance in the software test-bed presents a significant challenge. Phase 1 of MarRINav (in deliverable D3 [8]) has calibrated the 'SSv2' EGNOS model for maritime performance and validated this for locations within good coverage of many RIMS. However, questions remain about its validity near edge of service coverage (where the model's representation of EGNOS performance depends primarily on the number of RIMS contributing to the navigation solution). Careful consideration, in consultation with ESA experts, must be given to the further modelling of maritime EGNOS in future phases of MarRINav.

For the timescale of 2025 and beyond, in which the maritime A.1046 EGNOS service provision for integrity at system level may be enhanced by a maritime service for integrity at user level based on EGNOS V3, the combined operation of EGNOS and MRAIM will determine maritime GNSS integrity performance. Suitability of models for this future maritime EGNOS will need to be investigated in detail, examining possible extension and validation of 'SSv2' or the GLA Augmented GNSS Toolset (GAGT) or alternatives that may arise from the EGNOS V3 programme.

2.4 Physical test-bed

A regional physical test-bed should be implemented according to the modular design as described in section 2.2.2. The infrastructure elements will all be linked with a prototype operational communications network, supporting the flow of PNT-based information for the system-of-systems under test and the gathering of test data results. Additionally, independent reference data for PNT will need to be provided as a 'truth system' for comparison with the test data and determination of error characteristics.

2.4.1 Shore Infrastructure

The integration of GNSS (when available), eLoran and VDES R-Mode would form the core of the physical test-bed. This would require a one-off survey to map the eLoran Additional Secondary Factors (ASF) as a database for the test-bed region. It also requires shore-based infrastructure: transmitters, a local Differential Loran reference station and a single combined integrity monitoring station. The ASF map would be stored within the test vessels' receivers and the physical transmitters, differential station and integrity monitor would be linked by the two-way communications of the preliminary ODN to a bare-bones control centre.

The costs of system elements set against the test-bed budgets and funding sources (investigation of which are beyond the scope of this plan) will influence the extent to which the test-bed design may be implemented. As eLoran transmitters contribute one of the largest costs, reducing their number to a minimum within the test-bed would be attractive. Although 3 eLoran transmitters are required to derive the position (latitude, longitude) and time solution from eLoran, consideration could be given to implementing only one eLoran transmitter (additional to the existing transmitter at Anthorn) in the test-bed, given that eLoran positioning technology is itself relatively mature. The one additional transmitter would enable proof-of-concept for the TV mast infrastructure and synchronisation techniques mentioned in section 2.2.1. If a precise clock were available on-board the test vessel, then an eLoran position solution could be derived from just the two eLoran transmitters. Such a clock is expected to emerge in a suitable timescale from the UK Quantum Technologies (QT) programme. It is also noted here that the tightly-coupled integration of eLoran with VDES R-mode (if synchronised with eLoran to UTC) to derive a hybrid PNT solution can also be achieved with only a single additional eLoran transmitter.

2.4.2 Vessels and MSR

The test-bed should involve a number of vessels, appropriately equipped with a prototype multi-system receiver (MSR), ideally incorporating a real-time test version of Maritime Receiver Autonomous Integrity Monitoring (MRAIM). GLA have a number of vessels which are accustomed to fitting experimental equipment and participating in trials. Several major shipping lines and ports have also cooperated in such activities in the past. Many tests can be performed as a 'ride-along' activity on the vessel as it continues its principal duties, with minimal disruption to its day-to-day operation.

As a minimum, the prototype MSR fitted to a test vessel must be capable of receiving the radio navigation signals, digitising them and storing the data for off-line integration and analysis. Such equipment could be developed as an adaptation of a Software Defined Radio (SDR) receiver. Alternatively, it may be possible to acquire a prototype MSR from other ESA projects, subject to ESA and developers granting permission for the use of a suitable prototype equipment in exchange for a range of datasets gathered in the trials.

A method of portraying the PNT data on-board ship would help to visualise results during demonstrations. This would be particularly powerful if the test-bed were expanded to include the use of resilient, high-integrity PNT data in examples of e-Navigation services. A suitable portrayal mechanism may utilise an e-Navigation Prototype Display (ePD) as used previously in a number of maritime research projects (such as ACCSEAS and CAPITALS).

2.5 Proof-of Concept Demonstration

The physical regional test-bed, with results extrapolated to UK national coverage through use of the software test-bed, should aim to demonstrate proof-of-concept of the following eLoran capabilities for maritime positioning accuracy (95%) with integrity:

- 10 metre accuracy, applicable to 9 out of 10 major UK ports and their approaches
- 20 metre accuracy, applicable a major part of the UK exclusive economic zone (EEZ)
- 30 metre accuracy, throughout the entire UK EEZ for a hold-over period of at least 2 hours during which GNSS is degraded or unavailable.

With the inclusion of VDES R-Mode along with eLoran in the integrated navigation solution, the test-bed should demonstrate proof-of-concept for 10 metres accuracy for all major ports and potential capability for high-risk Traffic Separation Schemes (TSS), subject to the configurations and cooperation for the Channel / La Manche with France explained in D5 [1].

The combination of physical and software test-beds should aim to contribute to the demonstration of GNSS/EGNOS/MRAIM system and user level integrity and continuity of maritime positioning at the 10 m (95%) accuracy level, 25 m Horizontal Alert Limit and 10 s Time to Alarm. With integrity risks of the order of 10^{-5}, the variation of maritime conditions and ships which impact local GNSS signal reception would imply the need for impracticably large data sets to gain statistical significance of integrity results. Therefore, the proof-of concept activities will need to consider the approach to such formal validation for maritime safety and the role of real-world test data within that process.

The requirements listed above have been derived from IMO Resolution A.915, acknowledging that although these requirements need review, they remain the principal official statement of maritime requirements for general navigation, as well as a broad range of other maritime positioning applications. A broad summary of PNT requirements is provided in Appendix B of MarRINav deliverable D1 – maritime context and requirements.

The test-bed demonstrator should further aim to demonstrate the eLoran delivery of precise time to users in non-maritime sectors and applications throughout the UK. This should include precise timing delivery to better than:

- 500 nanoseconds throughout the UK for an internally (or externally) mounted antenna and without the use of differential timing reference stations;
- 100 nanoseconds throughout the UK with the use of differential timing reference stations, with an internally (or externally) mounted antenna.

3 Assumptions, Extension Possibilities and Timescales

3.1 Assumptions

This Outline Development Plan for the test-bed demonstrator makes the following assumptions:

- All shore-based infrastructure is located in UK territory so that the principal capability that results is entirely under UK sovereign control.
- The EGNOS V2 ‘maritime A.1046 service’ becomes operational in early 2022.
- Technical engagement with ESA experts supports discussion of the EGNOS V3 approach to potential future maritime services and of models for maritime EGNOS.
- Datasets for multipath signal reception on ships collected during the test-bed campaign may be extended with additional data from other ESA projects, subject to ESA agreement.
- Vessels can be fitted experimentally with prototype receivers as the IMO MSC.401(95) performance standard for a multi constellation multi system receiver (MSR).
- Models of the MSR and its test environment developed under other ESA projects could be made available for use in the test-bed, subject to ESA agreement.

3.2 Extension possibilities

The test-bed has possible extensions, subject to UK policy and international collaboration:

- The extension to eLoran signal transmissions from Sylt, in cooperation with the maritime authority of Germany (WSV) and the German government.
- The extension to VDES R-Mode signal transmissions from France, centred on Calais for coverage of the Channel, in cooperation with the maritime research authority of France (Cerema) and the French government.

3.3 Timescales

The timeline below in

Figure 9 illustrates that the implementation of this Outline Development Plan is expected to span a period of at least two years from mid-2020 to mid-2022 and beyond. Precision on timings will increase as this outline plan is developed into a more detailed plan and proposal for MarRINav Phase 2.

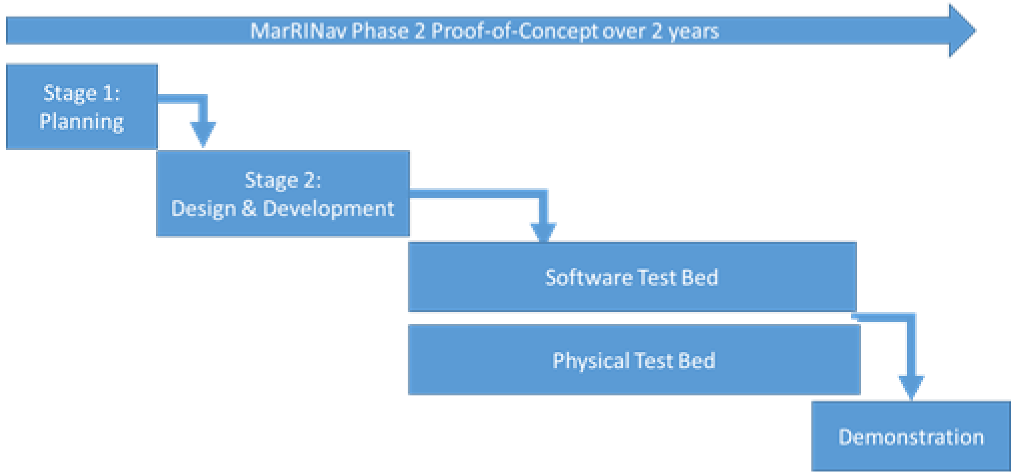

Figure 9: MarRINav Phase 2 timeline

4 Conclusions and Recommendation

An Outline Development Plan has been defined for further R&D needed for the evolution of the UK conceptual architecture for maritime resilient and high integrity PNT within UK CNI. The plan has been constructed with a staged approach, leading to the implementation of a local test-bed demonstrator for proof-of-concept of the hybrid system-of-systems solution. In its final phase, the plan aims to demonstrate a prototype infrastructure with associated radio navigation services for shipping and blue economy applications that could ultimately be scalable to UK national level with a service coverage area spanning the UK EEZ.

The five stages of the plan are:

- **Planning**: confirmation of objectives, elaboration of a detailed plan, specification of requirements and location assessment for the test-bed demonstrator.
- **Design and Development**: maturation of technologies within the system-of-systems solution, and modular design of the systems-of-systems following systems engineering principles.
- **Software Test-Bed**: models of technologies and prediction of hybrid service coverage areas to support physical demonstration and validation from real-world results.
- **Physical Test-Bed**: implementation of bare-bones demonstrator for proof-of-concept of the hybrid PNT solution.
- **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.

4.1 Recommendation

It is recommended that this Outline Development Plan be used as the basis of a proposal to the ESA NAVISP Programme Element 3 (National Interest), as a Phase 2 of the MarRINav project. Phase 2 is recommended to run for at least two years, from mid-2020 to mid-2022 and beyond, with a scope to be accommodated within the available budget of NAVISP Element 3 in accordance with the ESA Council of Ministers decisions taken in November 2019.

References

[1] MarRINav Deliverable D5, "Conceptual PNT Infrastructure", Version 2.0, dated 13th December 2019.

[2] IMO Resolution MSC.401(95) – 'Performance Standards for Multi-System Shipborne Radionavigation Receivers', Adopted 8 June 2015.

[3] MarRINav Deliverable D6, "MSR Integrity Report", Version 1.1, 18th October 2019.

[4] MarRINav Deliverable D4

[5] MarRINav Deliverable D9

[6] MarRINav Deliverable D1

[7] MarRINav Deliverable D3b

[8] MarRINav Deliverable D3

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