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GRAD Driving Innovation for Safer Maritime Navigation

VDES R-Mode Development

Technical Report

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A technical report on VDES R-Mode has been produced covering the following aspects of VDES R-Mode development: stakeholder and system requirements; candidate system architectures; coverage and performance modelling and experimental verification.

Executive Summary

Ranging mode (R-Mode) refers to the addition of a ranging capability to existing or new marine data transmissions. Two concepts for R-Mode are currently being studied by the international maritime community, based on the medium-frequency (MF) signals of the IALA Marine Beacon DGPS System, and the use of base station networks of the Automatic Identification System (AIS) and its planned successor, the VHF Data Exchange System (VDES). The focus of this project has been on the VDES variant of R-Mode.

The project has built on a feasibility study of VDES R-Mode performed by GRAD in FY17-18, it has further developed the system concept and conducted initial experiments to verify theoretical performance models developed previously. This work is very timely as there is an opportunity to incorporate elements of R-Mode functionality into the next revision of the ITU-R Recommendation on VDES, expected to be published in 2020.

More specifically, the following work has been undertaken as part of the project:

- A Stakeholder Requirements Document for VDES R-Mode has been compiled, which has been approved by the IALA ENAV Committee and circulated to the ARM, ENG and VTS committees for comments;
- The stakeholder requirements have been analysed and a System Requirements Document has been drafted to provide a firm basis for subsequent system design activities; at the time of writing, the document is being further developed by R-Mode experts within IALA and the R-Mode Baltic project;
- A high-resolution, terrain-specific VHF propagation model and a coverage and accuracy performance model for VDES R-Mode have been developed, capable of generating coverage plots for any user-defined geographical area anywhere in Europe.

Taking into consideration the locations of existing AIS base stations in the UK and Ireland, the project has then carried out an initial assessment of six candidate system architectures for VDES R-Mode. This has concluded that:

- System architectures that support the “bilateration” approach (that is positioning using signals from just 2 VDES base stations) have the potential to provide satisfactory R-Mode coverage across most of the GLA’ service area (assuming that all currently existing stations are upgraded to VDES);
- System architectures that use 3 or more signals to determine position would require a significant densification of the current base station network in order to provide adequate coverage;
- System architectures that use pseudorange-based positioning (that is where the shipborne equipment has to solve for an unknown clock bias) would require a substantial proportion of the R-Mode stations to be deployed off shore;
- System architectures that are based on active (two-way) ranging have some attractive features (such as no need for base station synchronization and the possibility to achieve satisfactory coverage using only land-based stations); however, such architectures result in a prohibitively high VDES datalink loading and therefore should not be considered further;
- System architectures based on hybrid ranging (using a combination of active and passive ranging, in conjunction with high-stability shipborne clock) may represent a good compromise between the achievable accuracy and impact on the VDES datalink; however, such architectures are likely to require relatively high-cost shipborne equipment;

- System architectures based on the combined use of passive ranging and a GNSS-calibrated high-stability shipborne clock may be a good solution where only a contingency[1] system is required;
- The IALA R-129 position accuracy target for port approaches, restricted waters and inland waterways of 10 m (R95) appears difficult to achieve with any of the architectures considered herein;
- The IALA R-129 position accuracy target for navigation in coastal waters of 100 m (R95) appears to be achievable.

A number of recommendations for future work have been identified and are detailed in the Recommendations section.

[1] IALA defines a *contingency* Positioning, Navigation and Timing system as one that allows safe completion of a manoeuvre, but may not be adequate for long-term use.

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1 Introduction

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 [1]. 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 Position, Navigation and Timing (PNT) data processing, MSC.1/Circ.1575 [2], [3].

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

The project has built on a feasibility study of VDES R-Mode performed by GRAD in FY17-18 [4] and has further developed the system concept. This work is very timely as there is an opportunity to incorporate elements of R-Mode functionality into the next revision of the ITU-R Recommendation on VDES, expected to be published in 2020 (the revision process is illustrated here in Figure 1).

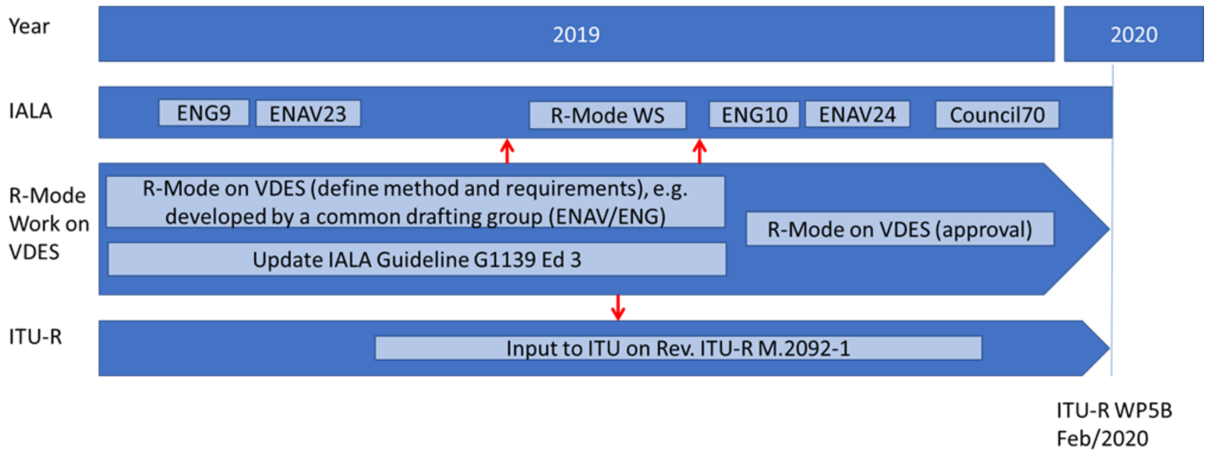

Figure 1: IALA-proposed roadmap for the development and standardisation of VDES R-Mode.

This project report is structured as follows: Section 2, along with Annex 1, provide the stakeholder requirements for VDES R-Mode, as agreed by the IALA e-Navigation Committee. Section 3 describes ongoing work to translate the stakeholder requirements into a set of system requirements, providing a firm basis for system design activities. Section 4 presents some preliminary system architecture considerations; 6 candidate system architectures are introduced and evaluated in terms of their ability to provide R-Mode coverage within the UK and Irish waters, the achievable positioning accuracy, likely equipment cost and other factors. The report concludes with a summary of the key findings and recommendations for future work.

2 Stakeholder Needs and Requirements

At the start of this project, no formally agreed set of stakeholder needs or requirements for VDES R-Mode (or any other flavour of R-Mode) was available. Therefore, the first objective was to review relevant IMO, ITU, IALA and other source documents to identify the stakeholder needs in relation to resilient PNT and compile a consolidated set of stakeholder requirements for VDES R-Mode. The results of this work were submitted to the IALA ENAV Committee and accepted as the basis for an IALA working paper [5] which is reproduced here in Annex 1. At the time of writing, the paper has been reviewed and approved by the IALA ENAV Committee and sent for comments to the ARM, ENG and VTS committees. It is anticipated that the document will be revised at the IALA Workshop on R-Mode in September 2019.

As discussed in more detail in Annex 1, VDES R-Mode could be configured to meet the requirements of a contingency[2] or backup[3] system, depending on design and the budget available (i.e. better clocks offer greater hold over but cost more). To be consistent with the Baltic Sea project, this work considers R-Mode as a contingency PNT system with a holdover capability of at least 2 hours, with a design goal of being capable of operating as a full backup to GNSS. VDES R-Mode should be capable of meeting the performance requirements for a GNSS backup applicable to navigation in coastal waters, as well as port approaches, restricted waters and inland waterways, as specified in IALA Recommendation R-129 [6] and summarized here in Table 1. The system should be interoperable with other alternative PNT systems (such as eLoran and MF R-Mode) and capable of interfacing with the IMO MSR [2].

Voyage Phase	R95 Accuracy (m)	Integrity			Availability (%)	Continuity over 15 min (%)	Fix Interval (s)
		Horizontal Alert Limit (m)	Time to Alarm (s)	Integrity Risk per 3 hours			
Coastal Waters	100	250	30	10^{-4}	99	N/A	15
Port approach etc.	10	25	10	10^{-4}	99	99.97	2

Table 1: Navigation performance requirements for VDES R-Mode [6].

3 System Requirements

The stakeholder requirements identified in [5] were analysed to establish a preliminary set of system requirements, which will eventually serve as the basis for design, development, verification and acceptance of the system. An early draft of the System Requirements Document is currently being reviewed by a group of IALA R-Mode experts. It is anticipated that this work will be progressed at the IALA Workshop on R-Mode in September 2019 and will be reported on in the FY19-20 VDES R-Mode report.

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[2] IALA defines a *contingency* PNT system as one that allows safe completion of a manoeuvre, but may not be adequate for long-term use.

[3] 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.

4 Preliminary Architecture Considerations

Since the stakeholder and system requirement specifications have not yet been finalised, it is currently not possible to establish a definitive system architecture for VDES R-Mode. Instead, several candidate system architectures were proposed, allowing the design trade space to be explored and providing an initial indication of the achievable coverage and performance.

4.1 System Overview

This section provides an overview of the system characteristics that are common to all the candidate architectures considered in this report.

The VDES R-Mode System will send accurately timed VHF transmissions from a network of land-based, and possibly offshore, Base Stations (BS). A shipborne VDES R-Mode Sensor (VRMS) will measure the timing (and other) parameters of the received signals and output the signal observables to an external PNT processor, such as the IMO MSR described in reference [2]. The PNT processor will then use the observables to determine the user's position, speed over ground and other navigation parameters.

VDES R-Mode should, as far as possible, use pre-existing shoreside infrastructure. It is anticipated that it will be possible to reuse pre-existing AIS/VDES BS antenna systems and other supporting technology. However, it is recognised that existing AIS BS hardware was not designed to provide the level of timing accuracy required for R-Mode and will generally not be suitable for the purpose [4]. Every cloud has a silver lining, though, and implementing R-Mode as part of VDES (rather than AIS) will have the advantage of a greater available bandwidth and therefore greater ranging accuracy.

In addition to new BS, new shipborne equipment will also be required to make use of the VDES R-Mode functionality. This is not yet commercially available, although it is expected that the R-Mode Baltic project will develop prototype units [7]; experimental VHF ranging equipment is also being developed by GRAD. It is anticipated that the VRMS will eventually be implemented as a module within the MSR, and that the MSR will provide a common clock synchronization signal for the VRMS, as well as other ranging system (such as MF R-Mode, eLoran and GNSS) modules, thus minimizing the number of measurements required to determine a position fix.

Other system components, such as Far-field Monitoring Stations (FMS) and one or more Monitoring and Control Stations (MCS) will be required in order to support the remote system monitoring and control functions; however, these components are likely to remain vendor-specific and therefore will not be considered further in this report.

4.2 Key Architecture Considerations

The key system architecture considerations included the following:

1. Ranging method;
2. Type of oscillator used to drive the shipborne clock; and
3. Positioning technique employed by the PNT processor.

The following three ranging methods were considered:

a) *Passive ranging*, where the shipborne equipment determines the range (or pseudorange[4]) to a BS by measuring the time of arrival of the signal transmitted by the BS;
b) *Active, or two-way, ranging,* where the shipborne equipment transmits a signal to the BS, receives a response and measures the round trip time to determine (true) range to the BS; and

[4] The term *pseudorange* is used when passive ranging measurements are made using a clock that is not synchronized with the system clock.

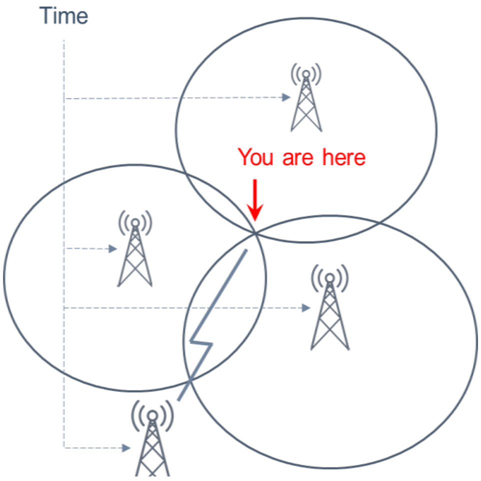

Figure 2: Positioning by (pseudo)ranging.

c) *Hybrid ranging*, which is a combination of active and passive ranging, as will be explained later.

In terms of the clock oscillators used in the VRMS / MSR, the following two options were considered:

a) A conventional crystal oscillator, such as a Temperature Compensated Crystal Oscillator (TCXO); vs.
b) A high-stability oscillator, such as a Rubidium or Chip-Scale Atomic Clock (CSAC).

It was assumed that a ship using a high-stability oscillator would either synchronize its clock using GNSS (when it is available), or use active ranging off a VDES BS to calibrate the clock. The former would provide only a limited holdover time (of perhaps a couple of hours) and would not strictly satisfy Annex 2, REQ-26. The latter would provide a practically unlimited holdover time in case of GNSS service disruption local to the ship.

Finally, three variants of the multilateration positioning technique were considered:

a) The classical multilateration approach, which involves measuring pseudoranges to points at four or more known locations to establish an unambiguous 2-D position fix and time;
b) *Trilateration*, using range measurements to at least three known points; and
c) "*Bilateration*", based on two range measurements (and additional information required in order to resolve the inherent position ambiguity).

The various aspects of the system architecture and their implications for the achievable coverage and performance are discussed in more detail in the sections below.

4.3 Candidate Architectures

Six candidate system architectures are described here, representing different combinations of the ranging methods, types of clock oscillator and positioning techniques introduced above (note that although there are 18 possible combinations of the mentioned system characteristics, only some of them result in a viable architecture).

4.3.1 System Architecture #1 (P-XO-MLAT)

The first candidate architecture uses a network of synchronized VDES BS to transmit accurately timed ranging signals. The shipborne equipment uses a conventional crystal oscillator (XO) and passive ranging (P) to measure a set of pseudoranges, and it determines position and time using classical multilateration (MLAT).

As can be seen from the diagram in Figure 2, with this architecture, the shipborne equipment will need to observe signals from **at least 4 R-Mode-enabled BS**, sufficiently distributed in azimuth around the location of the ship (note that two range measurements in two dimensions produce two

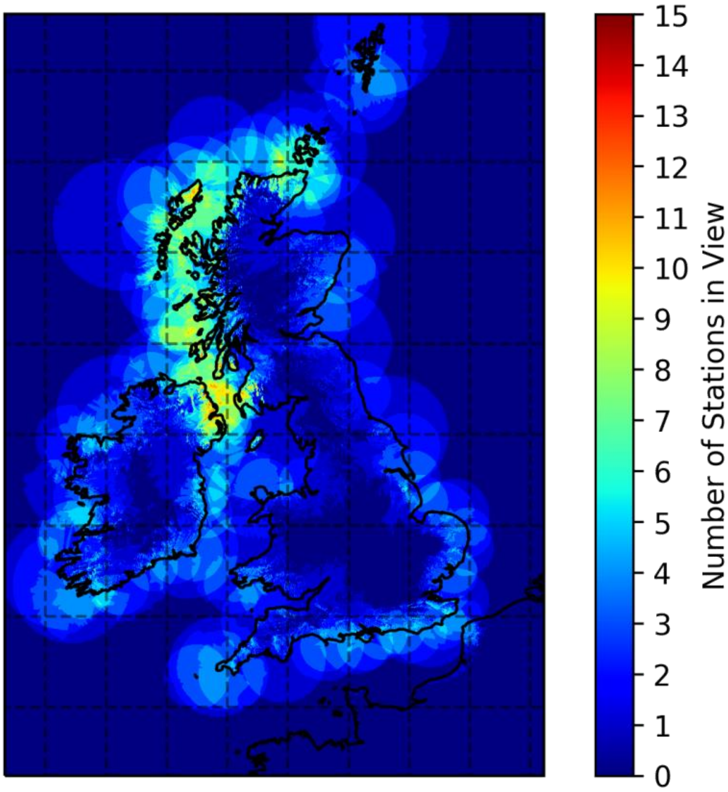

Figure 3: Number of available VDES BS
(based on locations of currently existing AIS BS).

circular lines of position that intersect in two places; a third range measurement is required to resolve the geometric ambiguity, and another measurement is needed to determine the pseudorange bias due to the unknown shipborne clock offset). At least five signals would be required for RAIM[5]-based integrity. It is worth noting that the minimum number of signals can be reduced by one if the geometric ambiguity is resolved using prior information (as discussed further in Section 4.3.5); however, in a short-range, 2D system, such as VDES R-Mode, the two ambiguous position solutions can be separated by a relatively short distance and this may complicate the ambiguity resolution process.

Figure 3 shows the number of BS available in the waters around the British Isles, based on the locations of all AIS BS currently operated by the GLA, MCA[6] and the Irish Coastguard (a total of 119 stations), and assuming that all stations have been upgraded to VDES. Individual station coverage areas were determined from the minimum carrier-power-to-noise-density ratio required for the successful demodulation of the most robust 100 kHz-bandwidth terrestrial VHF Data Exchange (VDE-TER) waveform (for more detail on the coverage prediction model, which was developed as part of this project, see Section 4.4). It can be seen from the plot in Figure 3 that there is a relatively high concentration of stations on the west coast of Scotland and along the Northern Ireland coast but most of the remaining parts of the UK and Irish coastline would have insufficient coverage for positioning if System Architecture #1 was used. This is more apparent from the plot in Figure 4, which shows the geographical area where at least 4 stations can be received.

Clearly, the use of this architecture would require a considerable densification of the existing network of AIS/VDES BS in order to achieve adequate coverage of the UK/Irish coastline.

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[5] *Receiver Autonomous Integrity Monitoring* is a way of providing user-level integrity by using an overdetermined system of measurements.
[6] Maritime and Coastguard Agency

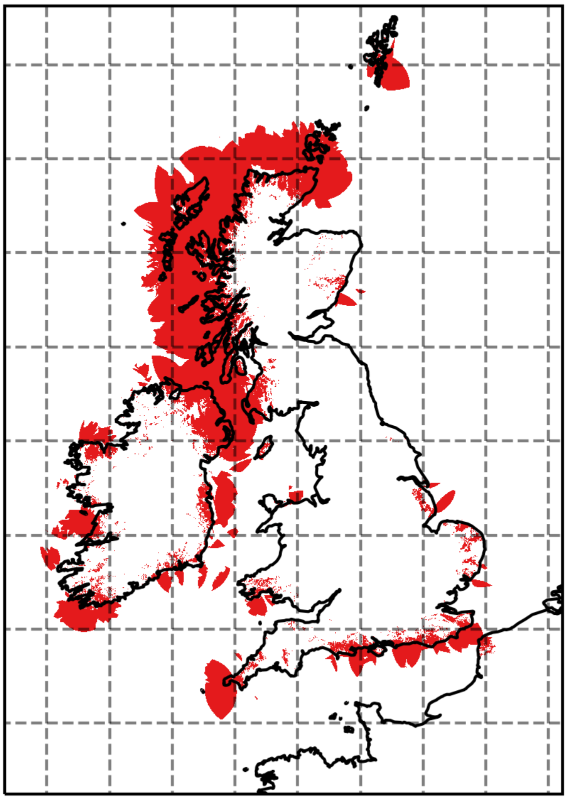

Figure 4: Simultaneous availability of at least 4 VDES BS
(based on locations of currently existing AIS BS).

A passive ranging, pseudorange-based system architecture such as the one described in this section appears to be the only architecture for VHF R-Mode that is currently being considered by the R-Mode Baltic project [7], [8].

4.3.2 System Architecture #2 (P-AC-3LAT)

Similarly to System Architecture #1, the second candidate architecture relies on a network of accurately synchronized VDES BS but it assumes that the shipborne equipment uses a GNSS-disciplined atomic clock (AC) to eliminate the (unknown) clock offset. This means that the ship can directly measure ranges to BS, rather than just pseudoranges, and consequently it only needs to observe signals from **3 R-Mode-enabled BS** in order to determine its position (this positioning mode will be denoted here as 3LAT; see also the diagram in Figure 2). At least four signals would be required for RAIM-based integrity.

Figure 5 shows the geographical area where at least 3 stations can be received. This represents a significant improvement compared to System Architecture #1; however, there would still be insufficient coverage along much of the coast of England and Wales, on the north-east of Scotland and parts of the Irish coast if this architecture were used.

In addition, this architecture provides only a limited holdover time in case of a GNSS failure, the length of which would be determined by the instability of the shipborne atomic clock (it is anticipated that a holdover time of several hours may be achievable with a commercially available Rubidium clock). Using the IALA terminology, System Architecture #2 represents a contingency, rather than a backup, system.

4.3.3 System Architecture #3 (A-XO-3LAT)

The third candidate architecture uses active (A) ranging to eliminate the effects of the shipborne clock offset, while also providing an unlimited holdover time (i.e. the architecture represents a true

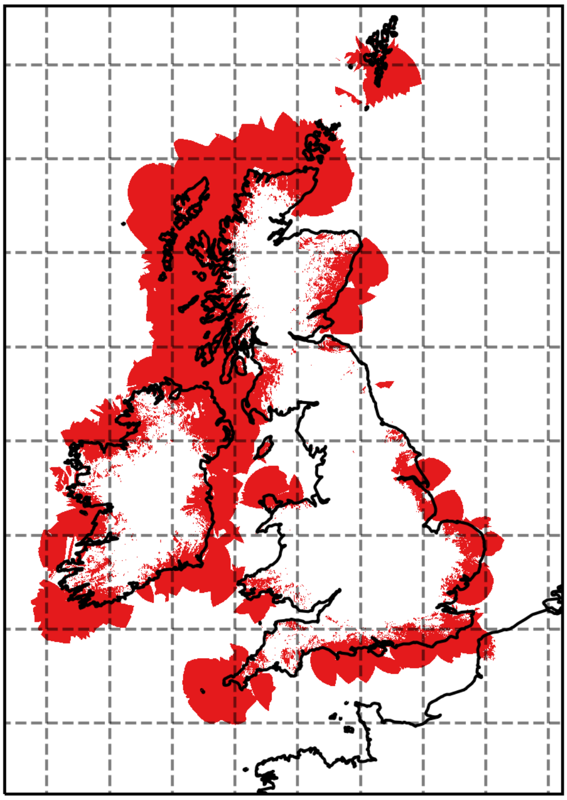

Figure 5: Simultaneous availability of at least 3 VDES BS (based on locations of currently existing AIS BS).

backup system). In active ranging, measurements are carried out in both directions between a ship and the BS. The measurements have equal-size and opposite timing offsets, so the ship-to-BS range can be obtained by taking their average. Consequently, no synchronization of the BS clocks is required and a position may be determined using just **3 R-Mode-enabled BS** (3LAT). Additionally, there is no need for an atomic clock on-board the ship; only a good quality crystal oscillator (XO) would be required. At least four signals would be needed for RAIM-based integrity.

Since the minimum number of signals is identical to that of System Architecture #2, the coverage areas for these two architectures would also be identical (see Figure 5).

System Architecture #3 certainly has some attractive features, as discussed above. However, with this architecture, the system could only serve a limited number of ships at a time, potentially putting a prohibitively high loading on the VDES datalink. The VDES radio channels are shared using a TDMA[7] scheme. There are 2,250 time-slots available per minute, per frequency channel. Assuming that each ship uses 2 x 3 time-slots for active ranging every 2 seconds (see Annex 2, REQ-21), then this represents 2 x 3 x 60 / (2 x 2,250) = 8% additional channel loading per ship. Consequently, the system could only support a maximum of 12 ships within the footprint of a given base-station triad (assuming that all channel capacity is allocated to R-Mode, and ignoring any additional R-Mode information that may need to be communicated, as well as resource re-use requirements potentially imposed by neighbouring VDES stations). Clearly, this is not acceptable.

4.3.4 System Architecture #4 (H-AC-3LAT)

The fourth candidate architecture is based around the idea of hybrid ranging (H). This method was devised with the aim of reducing the VDES channel loading, while retaining some of the advantages

[7] Time Division Multiple Access

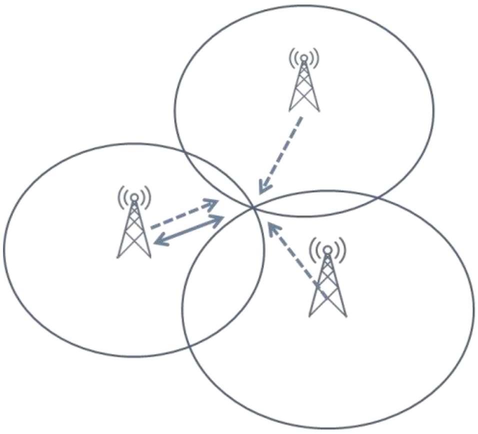

Figure 6: Hybrid ranging.

of System Architecture #3. Hybrid ranging refers to a combination of active and passive ranging, where the active ranging is used, relatively infrequently, to calibrate a shipborne atomic clock (A), and the passive ranging is then used for positioning, once the clock has been calibrated. This is illustrated in Figure 6.

Since passive ranging is part of the solution, all BS within the system must be accurately synchronized to a common time scale.

As with System Architecture #2 and System Architecture #3, ranges to at least **3 R-Mode-enabled BS** need to be measured; therefore, the coverage area would be as shown in Figure 5.

Due to the need to occasionally use active ranging, this architecture still has limited capacity; however, the maximum number of ships that could be supported would be considerably higher than with System Architecture #3.

4.3.5 System Architecture #5 (P-AC-2LAT)

The fifth candidate architecture makes it possible to **reduce the minimum number of signals required for positioning to only 2.** This leads to considerably improved coverage when compared to the previous architectures, as can be seen in Figure 7.

The architecture uses passive ranging (P) and therefore, again, requires that all BS are accurately synchronized to a common time scale. A GNSS-disciplined atomic clock (AC) is used on-board the ship in order to enable the shipborne equipment to directly measure ranges (rather than pseudoranges). Similar to System Architecture #2, this architecture represents only a contingency system.

Since only 2 range measurements are used to determine position (2LAT), the position solution is ambiguous (note that two circular lines of position will intersect in two places). It is assumed here that the position ambiguity is resolved by making use of prior knowledge of position (this could, for example, be the last available GNSS fix, or the previous successful R-Mode fix) and either (i) knowledge of the maximum distance travelable between position updates, or (ii) input from dead-reckoning sensors.

4.3.6 System Architecture #6 (H-AC-2LAT)

The sixth candidate architecture is identical to System Architecture #5 except that it uses hybrid ranging (H). This would enable the system to serve as a backup in case of a GNSS outage local to

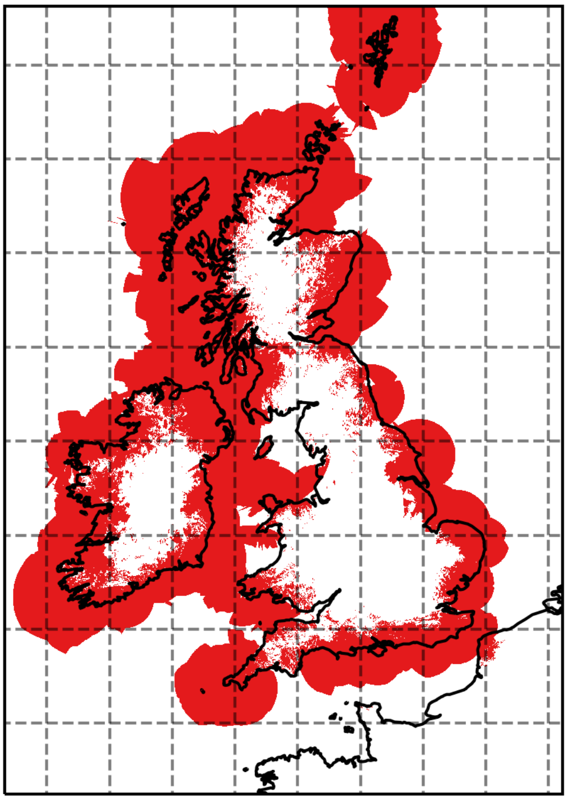

Figure 7: Simultaneous availability of at least 2 VDES BS (based on locations of currently existing AIS BS).

the ship (however, there still is a need for all BS to be synchronized to a common time scale with this architecture and this function may be affected by a long-term GNSS outage).

Since **at least 2 signals are required** to be able to determine the ship's position with this architecture, the coverage area would be as indicated in Figure 7.

4.4 Performance Evaluation of Candidate Architectures

4.4.1 Key Factors Affecting R-Mode Positioning Accuracy

The key factors affecting the achievable positioning accuracy in any ranging system are:

1. Ranging accuracy;
2. Number of available stations and their geometry with respect to the user; and
3. Positioning technique used.

These are discussed in turn below.

4.4.1.1 Ranging Accuracy

The accuracy of the individual (pseudo)range measurements depends on a great number of factors.

The impact of the VDES waveform and signal propagation characteristics on the achievable accuracy had been investigated as part of the AIS/VDES Development Project in FY17-18 [4], [9]. Theoretical lower bounds on the (one-way) ranging accuracy in an Additive White Gaussian Noise (AWGN) channel had been developed for all waveforms currently being considered for terrestrial VDES communications, as illustrated here in Figure 8. These bounds, together with a VHF signal propagation model and a model of the radio noise floor on-board ships can be used to predict the achievable ranging accuracy across the "communication" coverage area of any given VDES BS. This is illustrated in Figure 9. The models and assumptions used when producing the plot in Figure 9 are summarized in Table 2 and were used throughout the rest of this analysis.

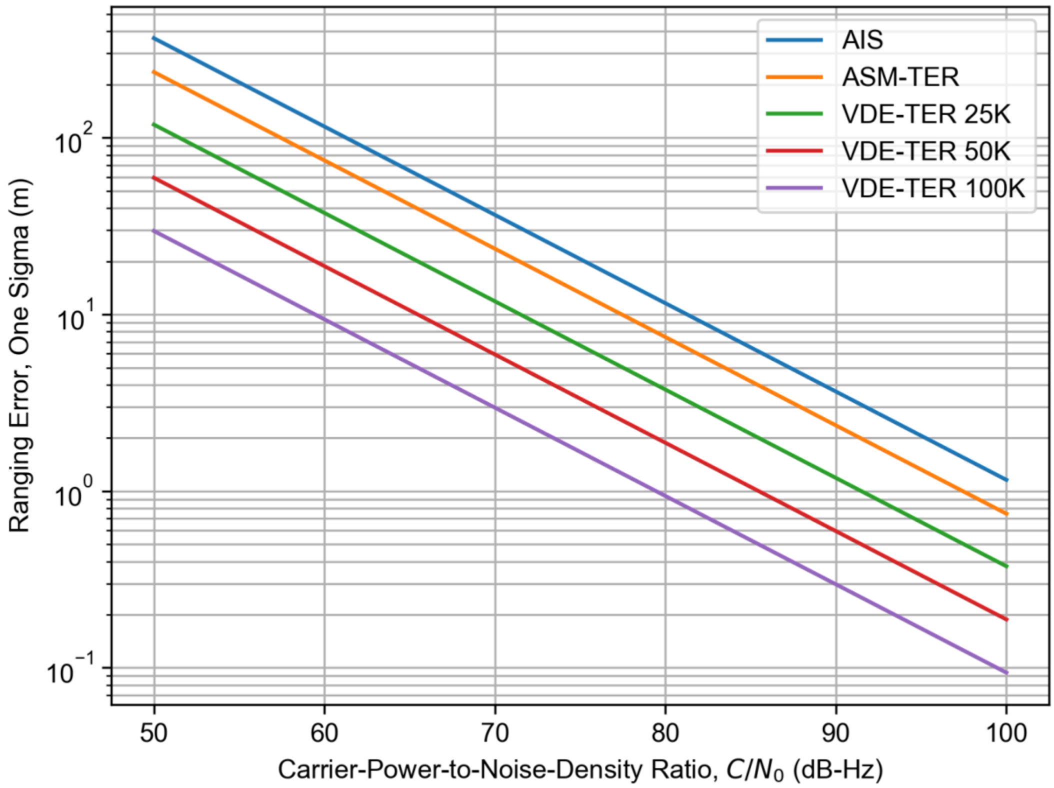

Figure 8: Achievable ranging accuracy as a function of the signal carrier-power-to-noise-power-density ratio for waveforms used in terrestrial VDES communications; one-slot transmissions.

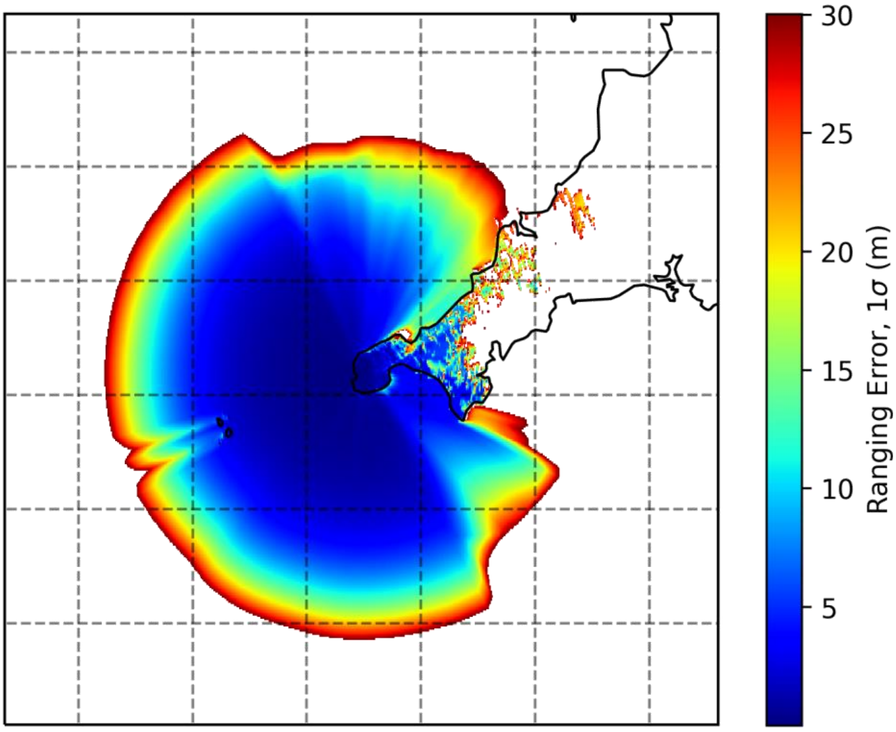

Figure 9: Achievable ranging accuracy for the St Just Depot station

Parameter	Value / Assumption	Notes
Ranging waveform	VDE-TER 100K	100 kHz-bandwidth VDE-TER waveform, using any of the standard VDE modulations; provides the best ranging performance out of all terrestrial VDES waveforms (see Figure 8)
Data symbols	Random (zero mean, mutually uncorrelated)	Ordinary user data transmissions are used for ranging rather than a fixed, dedicated data sequence
Duration of ranging signal transmission	Approximately 26.67 ms	1 VDES time slot
Base station synchronisation error and transmission timing jitter	Not modelled	Can be made sufficiently small; not the focus of this analysis
Transmitter power	12.5 W	Standard AIS/VDES high-power setting
Antenna feeder loss	1.2 dB	Based on a typical GLA' AIS installation; applied at either side of the radio link
Transmit antenna height above terrain	25 m	Assumed identical for all BS
Propagation channel model	**AWGN only, i.e. no multipath effects modelled**	Further work is required to establish a realistic multipath channel model
Path loss model	Rec. ITU-R P.1812	A terrain-specific VHF/UHF path loss model
Receive antenna height above sea water	10 m	Representative of an AIS antenna location on a small buoy tender, such as THV Alert
Antenna gain	0 dBd	Representative of a typical VHF end-fed dipole antenna; same value assumed for both transmit and receive antenna
Receive system noise figure (including external noise)	19 dB	Based on AIS equipment manufacturer and ITU data and own measurements; for a more detailed discussion, see [4]

Table 2: Summary of assumptions related to coverage and performance modelling.

It should be noted that the waveform design for VDES R-Mode is an active area of research. Alternative (dedicated) R-Mode waveforms have been proposed by the German Aerospace Centre (DLR) and by the National Institute of Telecommunications, Poland (NIT) and these may provide somewhat better performance than shown in Figure 8. The waveforms proposed by DLR and NIT are based around the use of the existing VDES modulations in conjunction with carefully designed data sequences. A further improvement could be achieved by designing a waveform that would simultaneously use the lower and upper parts of one or more duplex channels in the VHF maritime mobile band. The lower and upper legs of the duplex channels are separated from each other by

4.6 MHz. It can be shown that the effective bandwidth[8] of such a waveform could be up to 4.6π = 14.5 MHz. In theory, this should lead to a considerably improved ranging accuracy and multipath resistance when compared to the current waveforms which occupy at most 100 kHz of bandwidth. However, it should also be noted that this approach would likely require a change to the Radio Regulations, as the lower legs of the VDES channels are currently not approved for shore-to-ship use.

Some measurement error will occur due to various equipment imperfections, such as BS transmission timing jitter and residual shipborne clock drift and due to the (in)accuracy of the time source used for BS synchronization (for architectures where BS synchronization is required), These effects are implementation specific but can be made comparatively small if sufficient engineering effort is invested; therefore they are neglected in this analysis.

The choice of the ranging method also has an impact on the achievable accuracy. The lower bounds shown in Figure 8 are applicable to passive (one-way) ranging. Active (two-way) ranging involves making measurements in both directions and taking the average of the two. Consequently, the effects of any clock biases are eliminated, as explained earlier, and the variance of the measurement error is halved compared to that of a one-way measurement (assuming the stochastic components of the measurement error in the two component measurements are uncorrelated). Therefore the one-sigma measurement error for active ranging, $\sigma_{\hat{\rho},\mathrm{A}}$, was modelled as

$$\sigma_{\hat{\rho},\mathrm{A}} = \frac{\sigma_{\hat{\rho},\mathrm{P}}}{\sqrt{2}}.$$

where $\sigma_{\hat{\rho},\mathrm{P}}$ is the error that would be seen if measurements were made in only one direction, using passive ranging, which was modelled as described in report [4].

In hybrid ranging, the shipborne equipment first uses active ranging to synchronize a high-stability on-board clock to the system time scale. (True) ranges can then be measured using passive ranging, for as long as the on-board clock remains reasonably aligned with the system time. It was assumed that the strongest available R-Mode signal would be used for the clock calibration (so that the measurement error is minimized). The error in the hybrid ranging measurements will be a combination of the on-board clock synchronization error (determined largely by the achievable accuracy of the two-way, active ranging method, denoted here $\sigma_{\hat{\rho},\mathrm{A,strongest}}$) and the error in the passive measurement that would be seen if the on-board clock was perfectly synchronized, $\sigma_{\hat{\rho},\mathrm{P}}$. Therefore, as a first approximation, the measurement error for hybrid ranging was modelled as

$$\sigma_{\hat{\rho},\mathrm{H}} = \sqrt{\sigma^2_{\hat{\rho},\mathrm{A,strongest}} + \sigma^2_{\hat{\rho},\mathrm{P}}} = \sqrt{\frac{\sigma^2_{\hat{\rho},\mathrm{P,strongest}}}{2} + \sigma^2_{\hat{\rho},\mathrm{P}}}.$$

It should be emphasised that **all results presented in this report were obtained under the assumption of a pure AWGN (noise only, multipath-free) propagation channel.** Due to the relatively narrow bandwidth of the VDES signals (compare with that of GNSS signals and the inverse of the expected delay spread of the maritime VHF channel), it is anticipated that multipath propagation will have a significant impact on the ranging error in real-world settings; however, this remains to be verified by measurement.

4.4.1.2 Number of Available Stations and their Geometry

Under certain simplifying assumptions, the position accuracy in a ranging system (namely the DRMS[9] accuracy) can be modelled as a product of the ranging accuracy (the one-sigma ranging error expressed in meters) and a dimension-less multiplier, commonly referred to as the *Horizontal*

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[8] The effective bandwidth of a waveform is usually defined as the second moment of the frequency spectrum of the waveform divided by its energy. It can be shown that the ranging accuracy improves with increasing effective bandwidth.
[9] Distance Root Mean Square

Dilution of Precision (HDOP). For example, if the ranging error for each signal included in the position solution is 3 m and HDOP at the user's location is 2 then the DRMS positioning accuracy will be 6 m (corresponding to an R95 accuracy of approximately 6 x 1.73 = 10.4 m).

A mathematical derivation for HDOP, its relation to the position accuracy and the underlying assumptions were provided in presentation [10]. Some high-level observations and implications for the system architecture are noted below.

HDOP is a function of the number of stations used in the position solution and their distribution in space with respect to the location of the user. Broadly speaking, the higher the number of stations, the lower the HDOP and the better the positioning accuracy. The effects of the spatial distribution of stations depend on whether the system uses pseudoranging or (true) ranging to determine position.

The optimum station geometry for pseudorange-based positioning occurs when the stations are uniformly distributed in azimuth around the location of the user. This is illustrated for the case of 3 stations in Figure 11 (recall that 3 signals are sufficient for pseudoranging assuming that prior position information is available). HDOP (and hence position accuracy) with pseudorange-based positioning is severely degraded when the stations are located in a line, as shown in Figure 12, This means that **a system architecture based around pseudoranging** (such as System Architecture #1) **will likely require a substantial number of stations to be deployed off-shore** in order to provide satisfactory positioning performance.

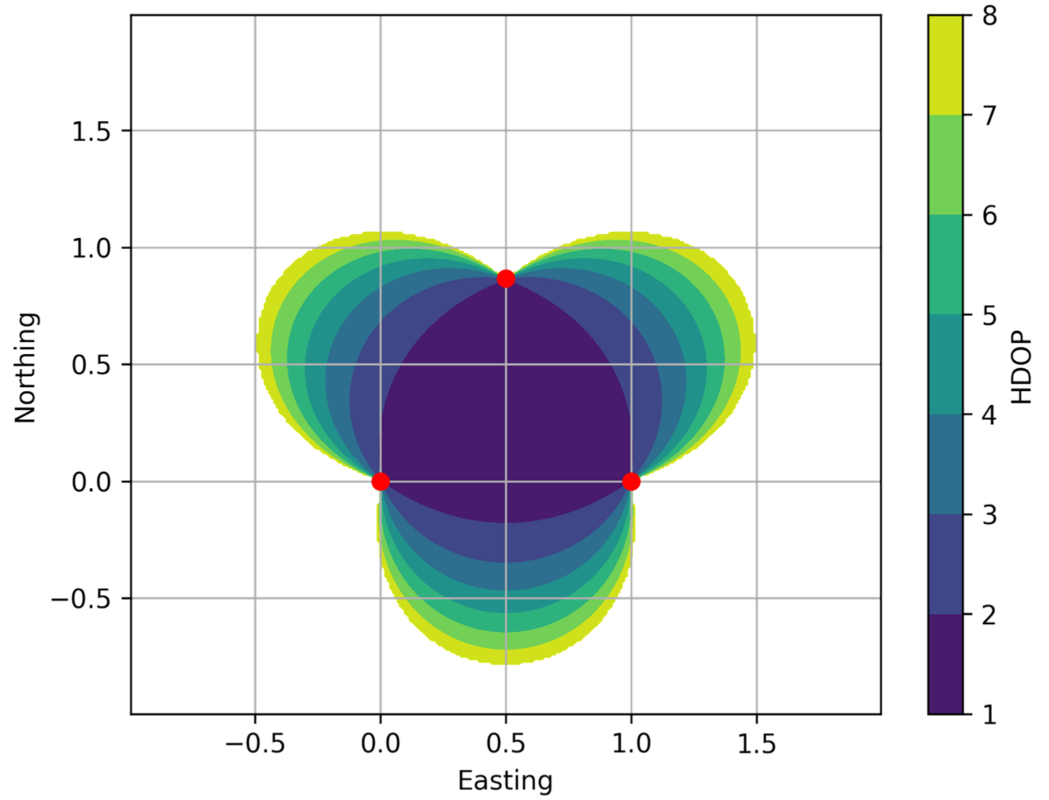

Figure 10: HDOP for pseudorange-based positioning with 3 stations (shown in red); optimum geometry is reached for a user located inside the station triad.

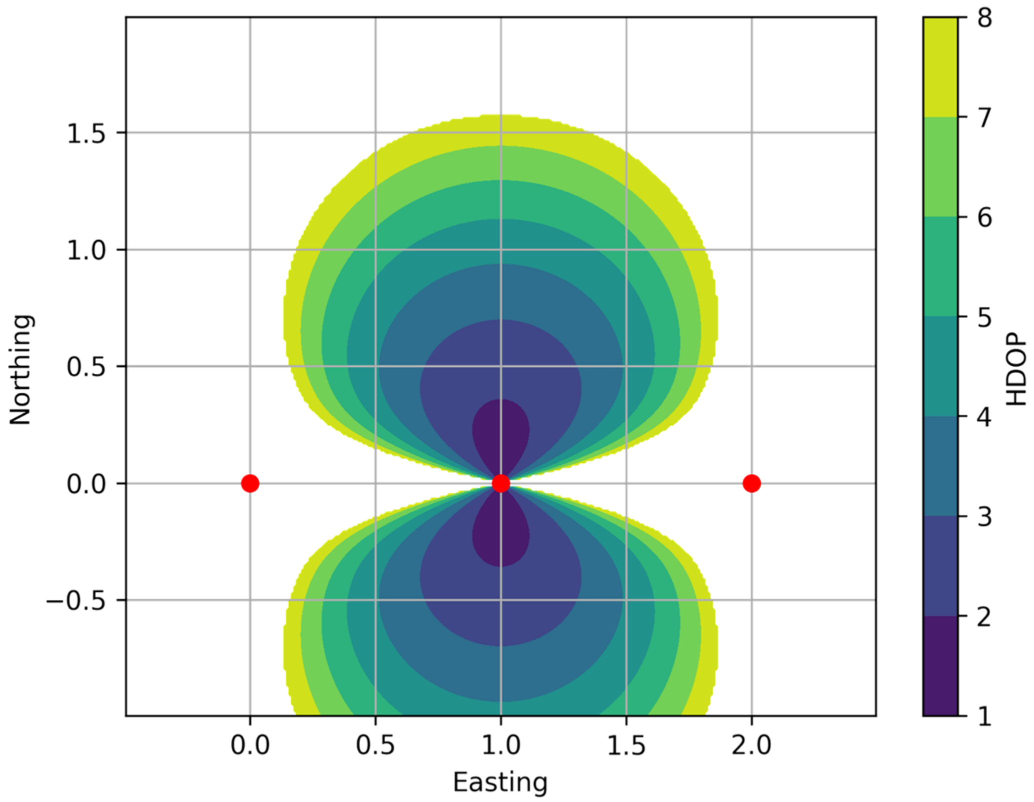

Figure 11: HDOP for pseudorange-based positioning with 3 stations located in a line.

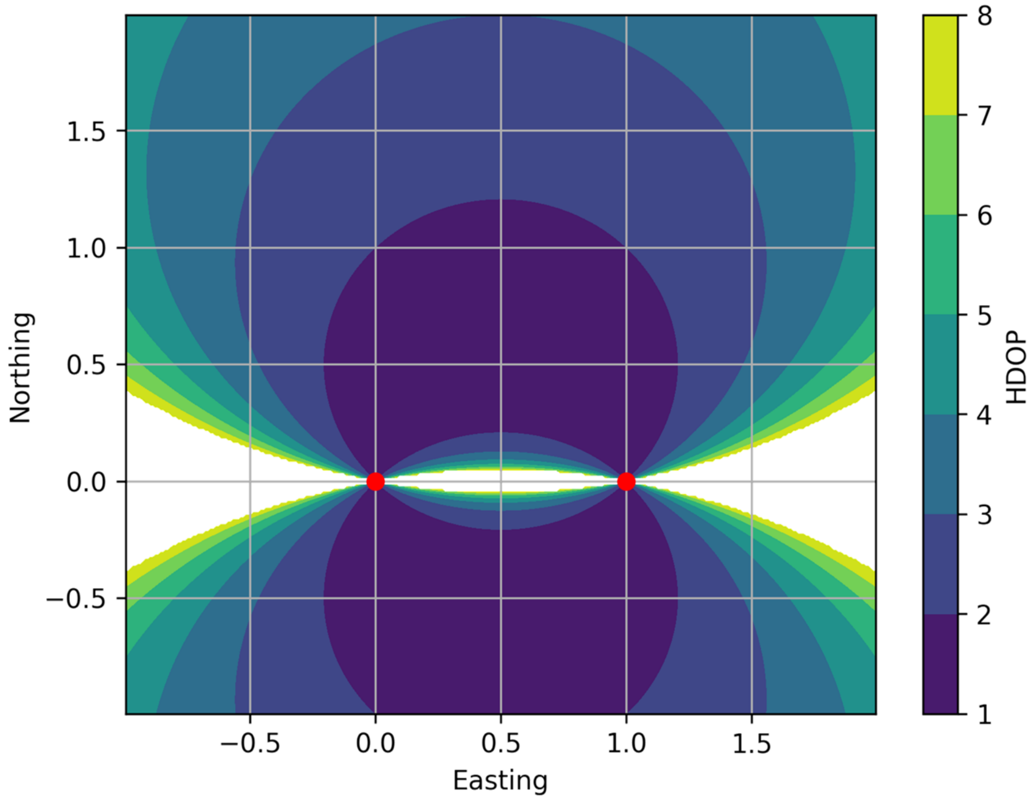

Figure 12: HDOP for (true) range-based positioning with 2 stations.

In range-based positioning (represented here by System Architecture #2 to #6), the position may be determined using one fewer station than required by pseudoranging. The optimum geometry with two range measurements is reached when the lines of sight to the two stations (or, equivalently, the two circular lines of position) subtend 90°. This is illustrated in Figure 13. With three range measurements, the optimum geometry occurs when the lines of sight to the stations are separated by either 120° or 60°. This means that **a range-based positioning system can provide satisfactory positioning performance across large areas of the sea using only land-based stations.**

4.4.1.3 Positioning Technique

As mentioned earlier, three variants of the multilateration techniques were considered in this work: “classical” multilateration using at least 4 pseudorange measurements; trilateration using at least 3 range measurements; and bilateration, based on only 2 range measurements.

With the first two techniques, the shipborne equipment can find the position solution by solving an overdetermined system of equations (note that, with either approach, there are at least one more measurements available than there are unknowns). It was assumed that the Weighted Least Squares (WLS) method would be used, which achieves improved positioning accuracy by assigning less weight to (pseudo)range measurements that are noisy.

With the third technique (bilateration), the system of equations to be solved (after linearization) is uniquely determined and is solved by direct matrix inversion (without any weighting being applied).

A derivation of mathematical expressions for the achievable positioning accuracy applicable to the above techniques can be found in references [10], [11].

4.4.2 Predicted Positioning Accuracy

Figure 13 to Figure 18 show accuracy coverage plots for the six candidate system architectures considered herein, generated using a VDES R-Mode coverage prediction model developed as part of this project. As can be seen from the plots, in areas where there are a sufficient number of stations available, the R95 position accuracy is in the region of 10 m to 20 m. The best accuracy performance is achieved with System Architecture #3 which uses active ranging; this is because active ranging effectively combines two one-way measurements, thereby averaging out the effects of measurement noise to some extent. It can also be seen that the architectures using hybrid ranging provide slightly lower accuracy than their passive ranging equivalents; again, that is expected as with hybrid ranging, the shipborne atomic clock synchronization would be derived from a VDES signal rather than from GNSS.

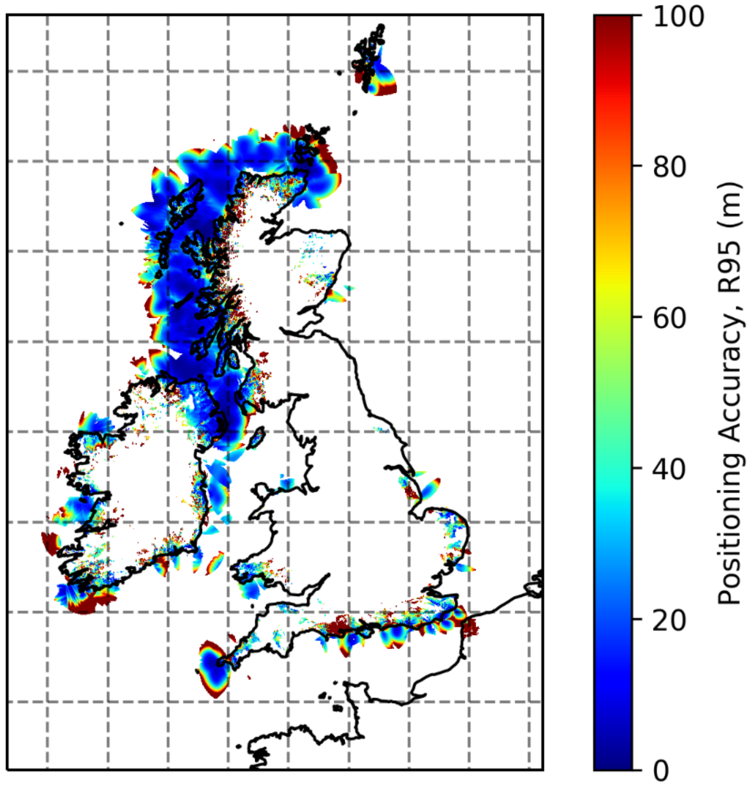

Figure 13: Positioning accuracy with System Architecture #1 (P-XO-MLAT).

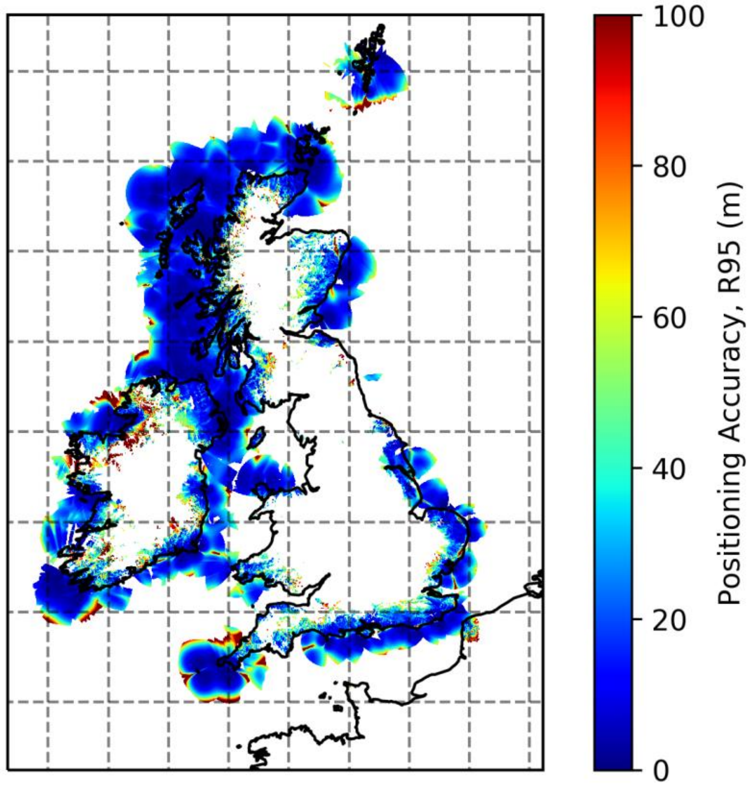

Figure 14: Positioning accuracy with System Architecture #2 (P-AC-3LAT).

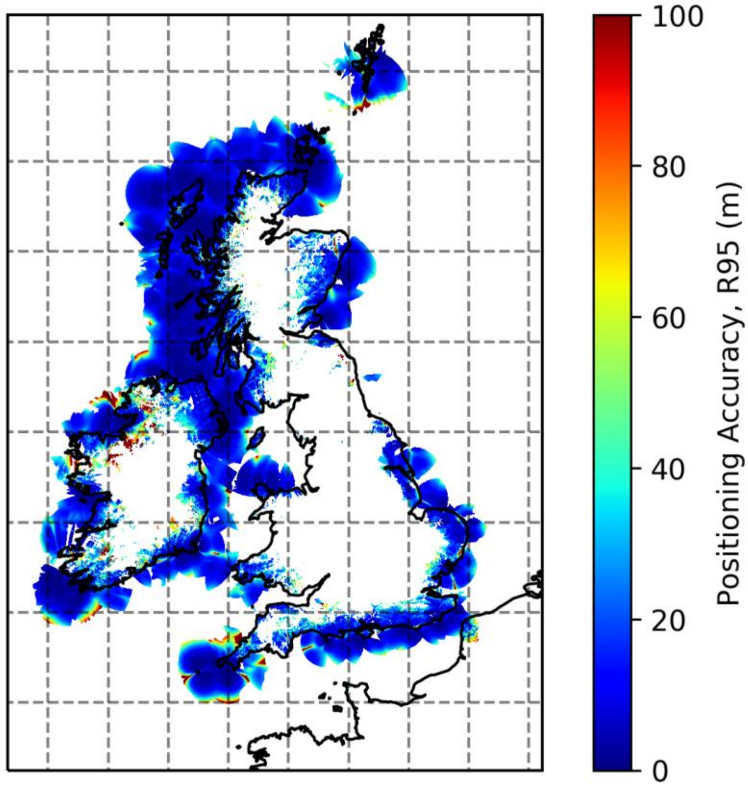

Figure 15: Positioning accuracy with System Architecture #3 (A-XO-3LAT).

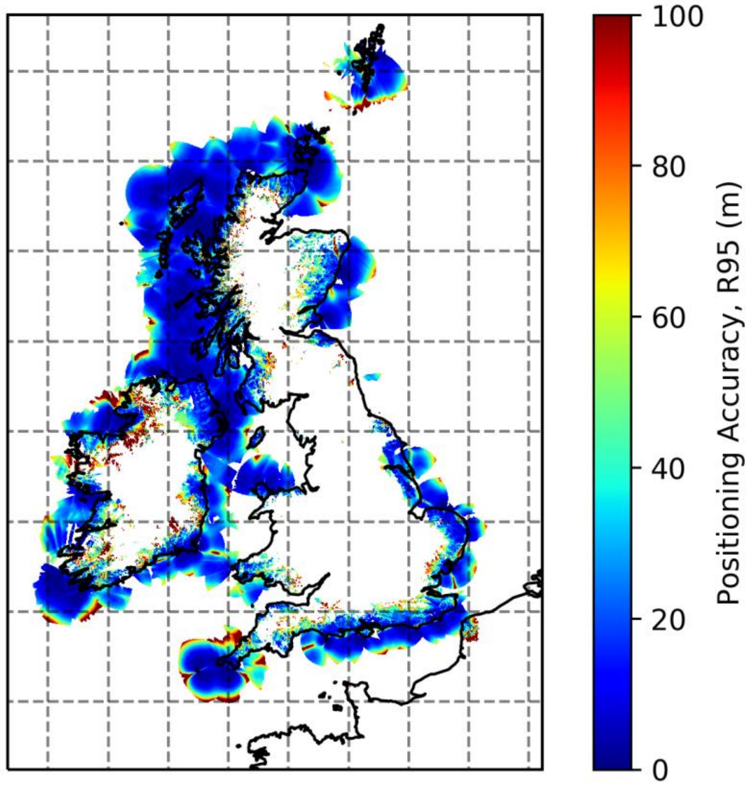

Figure 16: Positioning accuracy with System Architecture #4 (H-AC-3LAT).

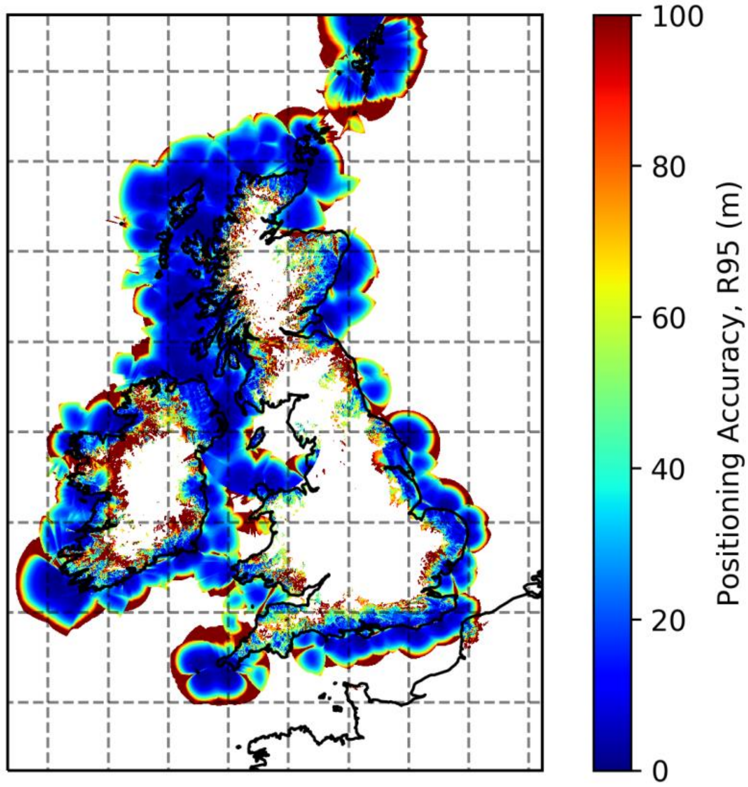

Figure 17: Positioning accuracy with System Architecture #5 (P-AC-2LAT).

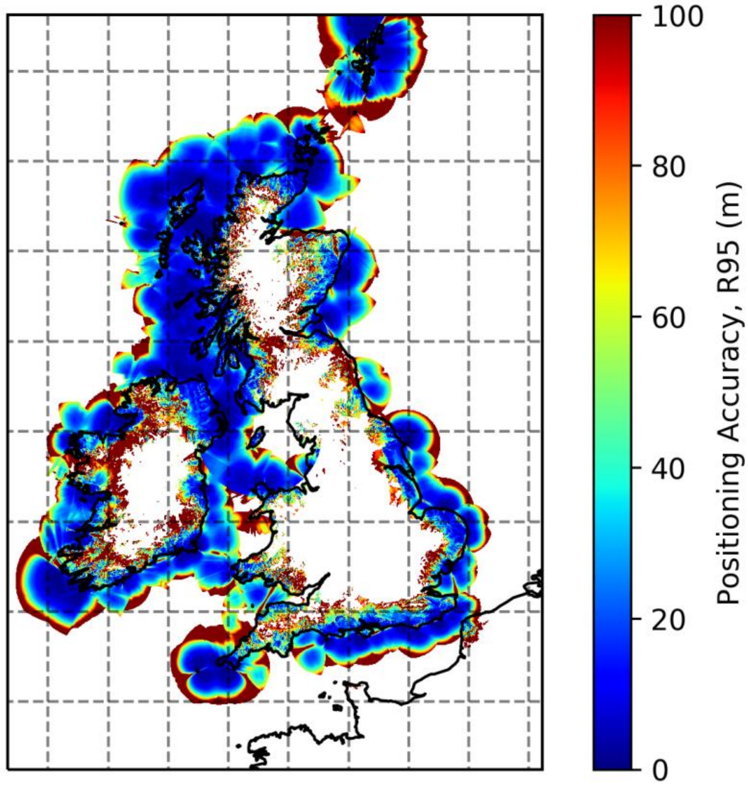

Figure 18: Positioning accuracy with System Architecture #6 (H-AC-2LAT).

4.4.3 System Architecture Comparison

Table 3 provides a summary of the key characteristics of the six candidate system architectures studied in this report. As can be seen from the table, only System Architecture #5 and #6 (that is those based on the bilateration approach) can provide satisfactory coverage and performance across the GLA' service area. Unfortunately, these are also the two architectures that are expected to have the highest cost of the shipborne VDES R-Mode equipment.

The remaining architectures would require a significant densification of the existing (AIS) BS network in order to provide adequate coverage along the UK/Irish coastline. This is especially true of System Architecture #1, which would require a substantial proportion of the BS to be deployed on off-shore platforms.

Candidate System Architecture	Accuracy Coverage vs. IALA R-129 Targets		Holdover Capability	Anticipated Cost of Shipborne Equipment	Impact on VDES Comms. Function
	Port Approach (10 m, R95)	Coastal Waters (100 m, R95)			
#1 P-XO-MLAT	Insufficient coverage along most of the coastline		Potential backup system[10]	Low	Low
#2 P-AC-3LAT	Isolated patches of coverage		Contingency system	Moderate	
#3 A-XO-3LAT			Backup system		High
#4 H-AC-3LAT				High	Moderate
#5 P-AC-2LAT		Good coverage along most of the coastline	Contingency system		
#6 H-AC-2LAT					

Table 3: System architecture comparison.

5 Conclusions

The following work has been undertaken as part of this project to support the development and international standardization of VDES R-Mode:

- A Stakeholder Requirements Document for VDES R-Mode has been compiled, which has been approved by the IALA ENAV Committee and circulated to the ARM, ENG and VTS committees for comments;
- The stakeholder requirements have been analysed and a System Requirements Document has been drafted to provide a firm basis for subsequent system design activities; at the

[10] This architecture can be considered a backup system (as defined in IALA R-129) as long as a time source independent of GNSS (such as eLoran) is used for BS synchronization.

time of writing, the document is being further developed by R-Mode experts within IALA and the R-Mode Baltic project;

- A high-resolution, terrain-specific VHF propagation model and a coverage and accuracy performance model for VDES R-Mode have been developed, capable of generating coverage plots for any user-defined geographical area anywhere in Europe.

Taking into consideration the locations of existing AIS base stations in the UK and Ireland, the project has then carried out an initial assessment of six candidate system architectures for VDES R-Mode. This has concluded that:

- System architectures that support the "bilateration" approach (represented here by System Architecture #5 and #6) have the potential to provide satisfactory R-Mode coverage across most of the GLA' service area (assuming that all currently existing stations are upgraded to VDES);
- System architectures that use 3 or more signals to determine position would require a significant densification of the current base station network in order to provide adequate coverage;
- System architectures that use pseudorange-based positioning (represented here by System Architecture #1) would require a substantial proportion of the R-Mode stations to be deployed off shore;
- System architectures that are based on active ranging (represented here by System Architecture #3) have some attractive features (such as no need for base station synchronization and the possibility to achieve satisfactory coverage using only land-based stations); however, such architectures result in a prohibitively high VDES datalink loading and therefore should not be considered further;
- System architectures based on hybrid ranging (represented here by System Architecture #4 and #6) may represent a good compromise between the achievable accuracy and impact on the VDES datalink; however, such architectures are likely to require relatively high-cost shipborne equipment;
- System architectures based on the combined use of passive ranging and a GNSS-calibrated high-stability shipborne clock (represented here by System Architecture #2 and #5) may be a good solution where only a contingency system is required;
- The IALA R-129 position accuracy target for port approaches, restricted waters and inland waterways of 10 m (R95) appears difficult to achieve with any of the architectures considered herein;
- The IALA R-129 position accuracy target for navigation in coastal waters of 100 m (R95) appears to be achievable.

6 Recommendations

It is recommended that future work should:

1. Conduct a measurement campaign to determine the achievable ranging performance under realistic propagation conditions and transmitter-receiver separations. In particular, the campaign should study the effects of:
    - Multipath signal propagation;
    - Changing environmental conditions (weather and sea state); and
    - Terrain topography and cover.
2. Update existing theoretical performance models for VDES R-Mode based on the results of step 1;

3. Model the coverage and performance for the system architectures considered in this work using the updated models from step 2; the cost estimates for each architecture (including the cost of the necessary infrastructure, shipborne equipment and operation) should also be refined;
4. Evaluate the candidate system architectures against the system (and stakeholder) requirements;
5. If necessary, make changes to the system architecture or requirements (in consultation with stakeholders) and repeat steps 3. and 4. until an acceptable architecture is found. In particular, the following aspects of the system architecture should be explored further:
    - The technical and economic feasibility of deploying BS on off-shore platforms, such as wind turbines;
    - The possibility of using high-stability shipborne clocks (such as Rubidium or Chip Scale Atomic Clock);
    - The possibility of using enhanced ranging waveforms that occupy both the lower and upper parts of the duplex VDES channels (as discussed in Section 4.4.1.1);
    - Integration with other ranging systems (such as eLoran and MF R-Mode) in the context of the IMO Multi-system Shipborne Radionavigation Receiver; and
    - The need for cryptographic authentication of the VDES R-Mode signal.
6. Identify characteristics of the base station and shipborne equipment that will need to be specified in the ITU-R Recommendation on VDES and/or IEC test standards for VDES and develop the appropriate specifications;

References

[1] P. D. Groves, *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*. Artech House, 2008.

[2] IMO, 'Performance Standards for Multi-system Shipborne Radionavigation Receivers', Resolution MSC.401(95), Jun. 2015.

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

[4] J. Safar, 'AIS/VDES R-mode Development', GLA, R&RNAV, Technical Report RPT-29-JSa-18, v.1.1, available as ENAV22-9.2.11, Aug. 2018.

[5] IALA, 'VDES R-Mode Stakeholder Requirements', IALA ENAV23, Singapore, Working Document ENAV23-12.1.15, Apr. 2019.

[6] IALA, 'GNSS Vulnerability and Mitigation Measures', Recommendation No. 129, Dec. 2012.

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[11] J. Safar, 'Analysis, Modelling and Mitigation of Cross-Rate Interference in Enhanced Loran', PhD Thesis, Czech Technical University, Prague, 2014.

[12] A. Dammann and R. Raulefs, 'R-mode Waveform Proposals', presented at the IALA ENAV WG3 Inter-sessional Meeting, Yiwu, China, Jul-2018.

[13] G. Johnson and P. Swaszek, 'Feasibility Study of R-Mode Using AIS Transmissions', ACCSEAS, Aug. 2014.

[14] G. Johnson and P. Swaszek, 'Feasibility Study of R-Mode Using AIS Transmissions', ACCSEAS, May 2014.

[15] J. Safar, D. Haley, A. Pollok, R. Luppino, A. Grant, and N. Ward, 'VDES Channel Sounding Campaign', General Lighthouse Authorities of the UK and Ireland, 2014.

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Annex 1 – VDES R-Mode Stakeholder Requirements

VDES R-Mode Stakeholder Requirements

1 SUMMARY

1.1 Purpose of the document

This document provides a summary of the VDES R-Mode stakeholder requirements and is intended as a basis for discussion and further development of the concept. These requirements are not complete and further collaborative work is required to develop a full set of stakeholder needs, stakeholder and system requirements.

1.2 Related documents

See the 'References' section below.

2 BACKGROUND

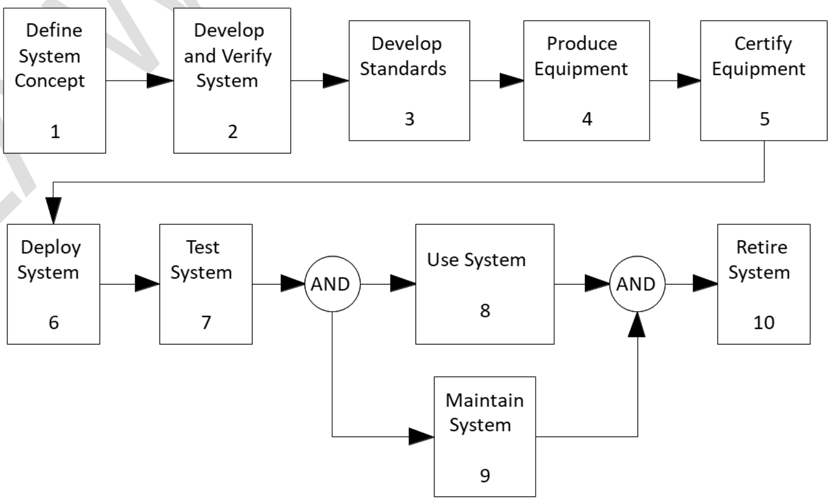
At recent meetings, the ENG and ENAV committees have discussed the possibility of using VDES for ranging (R-Mode). Several working documents and liaison notes have been produced on the topic, addressing various aspects of the concept. The authors of this paper have reviewed the available sources and compiled a list of stakeholder requirements for VDES R-Mode. It is hoped the information contained here will help establish a common understanding of VDES R-Mode among all stakeholders and serve as a basis for further development of the concept.

This document addresses the externally observable characteristics of the VDES R-Mode system. Characteristics of the internal system components (i.e. the system requirements) will be captured in a separate document as the concept evolves.

3 DISCUSSION

3.1 System Context

Figure 1 shows the anticipated stages of the VDES R-Mode system "life cycle". Each stage will likely see a different group of stakeholders interacting with the system, giving rise to different sets of requirements. This paper focuses mainly on stage 8 – 'Use System' as this is expected to provide the most valuable insights into the intended functionality and required performance of the system; however, it is important that further work consider the rest of the life cycle in more detail in order to obtain the complete picture.

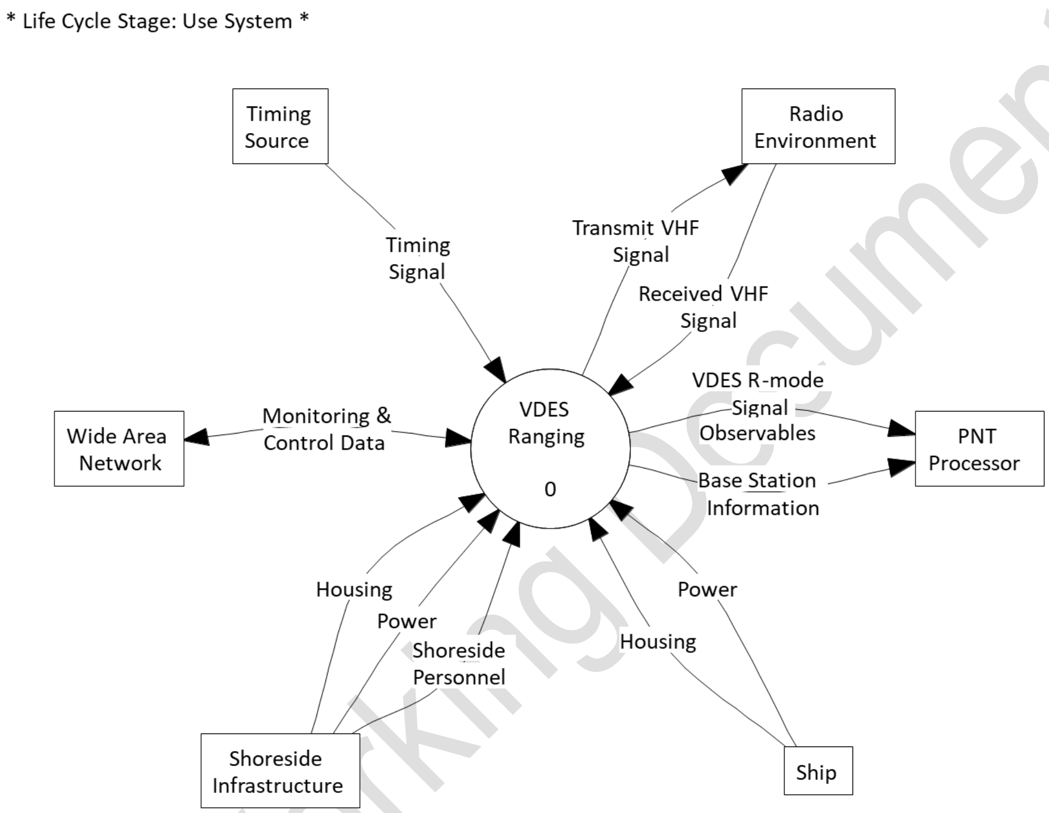


Anticipated stages of the VDES R-Mode system "life cycle".

Figure 2 then shows a preliminary context diagram for the 'Use System' life cycle stage. VDES R-Mode sends accurately timed VHF transmissions and measures the timing (and possibly other) parameters of the received signals. The measured observables are output to an external Position, Navigation and Time (PNT) processor, which determines the user's position, speed over ground and other navigation parameters.

VDES R-Mode should, as far as possible, use pre-existing shoreside infrastructure, including shore stations and monitoring and control centres, and pre-existing AIS/VDES shipborne installations. Monitoring and control data is likely to be carried via pre-existing wide area networks.

VDES R-Mode is synchronised to an external timing source traceable to a common time scale in order to facilitate interoperability with other PNT systems.



Preliminary VDES R-Mode system context diagram.

3.2 Stakeholder Identification

The following table lists the key stakeholders in the VDES R-Mode system and their respective anticipated roles.

Key stakeholders in the VDES R-Mode system.

Stakeholder	Role
IMO	Provides performance standards for PNT systems
ITU	Provides the Radio Regulations and other related documents; Produces the technical specification for VDES
IALA	Provides operational requirements for VDES R-Mode; Provides input to the technical specification for VDES
Shore Authorities	Provide operational requirements for VDES R-Mode; Provide shoreside infrastructure for VDES
Ship side	Provide operational requirements for the use of VDES R-Mode; Provide input into training requirements for the use of VDES R-Mode

Stakeholder	Role
Ship owners (ICS)	Provide, a position in conjunction with IMO, on carriage requirements.
GNSS Operators	Provide technical expertise with respect to GNSS vulnerabilities and GNSS time transfer applications
CIRM / Equipment Manufacturers	Provide technical expertise with respect to VDES; Conduct market research; Produce VDES equipment; Integrate VDES R-Mode into a resilient PNT solution
IEC ETSI RTCM	Develop test standards for VDES equipment Develop test standard for resilient PNT solution
Test Houses	Certify VDES equipment
R-Mode Baltic Project	EU-funded project aiming to set up an R-Mode test bed in the Baltic Sea region; Provides technical expertise with respect to VDES R-Mode; Produces prototype VDES R-Mode equipment; Conducts tests of the VDES R-Mode equipment / system

3.3 Stakeholder Requirements

Appendix 1 contains a list of stakeholder requirements extracted from the sources listed in the 'References' section. The requirements were categorised into several groups, such as functional, coverage, performance and a number of other non-functional requirements categories. Each requirement was assigned a priority as one of: Mandatory, High, Medium or Low.

Each requirement also has a status indicating the maturity of the requirement; permissible values are: New (the requirement has been captured from an external source), Ready (the requirement has been cleaned of any ambiguous statements and characterised), Checked (the requirement has been checked by the project team[11]), Review (the requirement is being reviewed by stakeholders), Agreed (the requirement has been accepted by stakeholders), Rejected (the requirement has been rejected by stakeholders and is to be reworked) and Deleted (the requirement is no longer needed).

The functional requirements were largely derived from the IMO Resolution MSC.401(95), 'Performance Standards for Multi-System Shipborne Radionavigation Receivers' [2] and the draft 'R-Mode Baltic – Baseline and Priorities' document [8].

The coverage and performance requirements are based on statements provided by the IALA ARM Committee in Liaison Note [16], the R-Mode Baltic document [8] and the IALA Recommendation R-129, 'GNSS Vulnerability and Mitigation Measures' [6]. R-129 provides a useful categorisation of potential alternative PNT systems:

> 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.

[11] 'Project team' in this context is internal GLA, but all aspects are open to wider international discussion and collaboration.

A *contingency system* allows safe completion of a manoeuvre, but may not be adequate for long-term use.

The R-Mode Baltic document [8]provides the following statements with respect to the above categories:

'The R-Mode project […] is intended as a backup system, or in between a contingency and backup system, to GNSS.

'it is assumed that R-Mode should be available for at least 2 h after GNSS has failed within the R-Mode accuracy requirement.'

The 2h window is derived from a. finishing manoeuvres is expected to finish within 2 hours and b. Rubidium clocks are stable for 2-6 hours, therefore a minimum time of 2 hours was set

In addition, ARM states that [16]:

'R-Mode (of any variety) should be considered as a "backup" to GNSS as defined in R-129 as the full functionality of GNSS is not required and R-Mode is therefore not considered as a fully "redundant" system.'

Therefore, this specification considers VDES R-Mode to be a contingency system with a holdover capability of at least 2 hours, with a design goal of being capable of operating as a backup.

ARM further provided the following statements with respect to the performance requirements of R-129 [16]:

'The backup requirements of R-129 are derived from IMO A.915(22) and as such would be difficult to revise in the timescale of this response. ARM considers that a further wider consideration of requirements for backup systems is needed (and also primary systems), but this is beyond the scope of ARM and indeed IALA and would require the considered debate within other bodies such as the IMO. In the timescales of this response however, ARM considers that the requirements remain valid';

Therefore, this specification adopts the performance requirements for a backup system stated in R-129.

R-129 specifies different requirements for different phases of voyage. These include ocean, coastal waters, port approaches and ports. With respect to the voyage phase, the R-Mode Baltic document [8] states:

'A global coverage is not possible with R-Mode due to the selected carriers (AIS and MF), but a global harmonization, in line with the e-Navigation concept, is important. The highest risk for degradation of the signal due to intentional and unintentional jamming is expected to be in coastal waters. R-Mode, as a system, is designed for coverage in coastal waters.'

'The system should support port approaches and navigation in restricted waters.'

Therefore, this specification adopts the R-129 performance requirements applicable to navigation in coastal waters as well as port approaches, restricted waters and inland waterways (but not the requirements for navigation in ocean waters and ports).

Further non-functional requirements were extracted from documents prepared by ENAV WG3, the ITU Radio Regulations and the sources referenced previously.

4 REFERENCES

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[2] M. Dziewicki, 'R-Mode Baltic - Baseline and Priorities', Sep. 2018.

[3] IALA ARM, 'VDES R-Mode System Requirements', Liaison Note to IALA ENG and ENAV, Oct. 2018.

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5 ACTION REQUESTED OF THE COMMITTEE

The ENAV and ENG committees are requested to review the stakeholder requirements listed in Appendix 1 and provide comments (and any additional requirements) to ENAV WG3 (Digital Communication Systems).

APPENDIX 1 VDES R-MODE STAKEHOLDER REQUIREMENTS

Key	Name	Identity	Requirement Details	Comments	Priority	Status	References
1	**Functional**	REQ-2				Accepted	
1.1	**Provide VDES R-Mode Base Station Information**	REQ-42				Accepted	
1.1.1	**Base Station Almanac**	REQ-30	The system shall provide to an external, shipborne PNT processor information on the identity and location of the VDES R-Mode Base Stations.	Each station should transmit information at least for itself and neighbouring stations.	Mandatory	Accepted	R-Mode Baltic - Baseline and Priorities (Draft) [2]
1.1.2	**Base Station Health**	REQ-15	The system shall provide to an external, shipborne PNT processor a "station safe to use"/"do not use" information for each Base Station within the system.		Mandatory	Accepted	R-Mode Baltic - Baseline and Priorities (Draft) [2]
1.1.3	**Base Station Signal Quality**	REQ-31	The system shall provide to an external, shipborne PNT processor information on the quality of the VDES R-Mode ranging signal such that the processor can obtain a measure of accuracy and integrity of the position solution derived from the VDES R-Mode observables.	Should include estimated clock synchronisation error, BS position accuracy, etc.	Mandatory	Accepted	Internal GLA Discussions
1.2	**Provide VDES R-Mode Observables**	REQ-41				Accepted	
1.2.1	**UTC**	REQ-11	The system shall provide to an external, shipborne PNT processor VDES R-Mode observables such that the processor could determine UTC to within one tenth of a second. For the purpose of this specification, it is assumed that the external processor may also use inputs from other PNT systems (but not to the exclusion of VDES R-Mode).		Mandatory	Accepted	IMO Resolution MSC.401(95) [1]
1.2.2	**Position**	REQ-8	The system shall provide to an external, shipborne PNT processor VDES R-Mode observables such that the processor can estimate the ship's geodetic horizontal position (latitude, longitude) in		Mandatory	Accepted	IMO Resolution MSC.401(95) [1]

Key	Name	Identity	Requirement Details	Comments	Priority	Status	References
			accordance with the World Geodetic System revision 1984 (WGS84). For the purpose of this specification, it is assumed that the external processor may also use inputs from other PNT systems (but not to the exclusion of VDES R-Mode).				
1.2.3	**Course over Ground**	REQ-9	The system shall provide to an external, shipborne PNT processor VDES R-Mode observables such that the processor can estimate the ship's course over ground (COG). For the purpose of this specification, it is assumed that the external processor may also use inputs from other PNT systems (but not to the exclusion of VDES R-Mode).		Mandatory	Accepted	IMO Resolution MSC.401(95) [1]
1.2.4	**Speed over Ground**	REQ-10	The system shall provide to an external, shipborne PNT processor VDES R-Mode observables such that the processor can estimate the ship's speed over ground (SOG). For the purpose of this specification, it is assumed that the external processor may also use inputs from other PNT systems (but not to the exclusion of VDES R-Mode).		Mandatory	Accepted	IMO Resolution MSC.401(95) [1]
2	**Coverage**	REQ-3				Accepted	
2.1	**Coastal Waters**	REQ-43	The system shall be capable of being used for navigation in coastal waters.		Mandatory	Accepted	R-Mode Baltic - Baseline and Priorities (Draft) [2]
2.2	**Port approaches, Restricted Waters, Inland Waterways - Goal**	REQ-44	The system should, as a goal, be capable of being used for navigation in port approaches, restricted waters and inland waterways.	There is no common, accepted, definition of where the boundary is between coastal waters and port approach. Search IMO SOLAS, Reg. V, and Circulars.	High	Accepted	R-Mode Baltic - Baseline and Priorities (Draft) [2]

Key	Name	Identity	Requirement Details	Comments	Priority	Status	References
3	**Performance**	REQ-4				Accepted	
3.1	**Position Accuracy - Coastal Waters**	REQ-12	When the system is used for navigation in coastal waters, the Horizontal Position Accuracy of the externally estimated position solution shall be at most 100 m, 95%.		Mandatory	Accepted	IALA R-129 [4]
3.2	**Integrity - Coastal Waters**	REQ-13	When the system is used for navigation in coastal waters, the Integrity Risk of the externally estimated horizontal position solution shall be at most 1e-4 over a period of 3 hours, with a Horizontal Alert Limit (HAL) of 250 m. Note: The continuity requirement (REQ-20) uses a time interval of 15 minutes. For compatibility reasons, it would be beneficial to use the same time interval for both the integrity and continuity requirements.		Mandatory	Accepted	IALA R-129 [4]
3.3	**Time to Alarm - Coastal Waters**	REQ-14	The Base Station Health information shall be provided in such a manner that mariners using the system for navigation in coastal waters can be warned of a system fault within 30 seconds of the fault occurring.		Mandatory	Accepted	IALA R-129 [4]
3.4	**Availability - Coastal Waters**	REQ-16	When the system is used for navigation in coastal waters, the Availability of the externally estimated position solution shall be at least 99%.		Mandatory	Accepted	IALA R-129 [4]
3.5	**Fix Interval - Coastal Waters**	REQ-17	When used for navigation in coastal waters, the system shall provide new signal observables to the external processor at least once every 15 seconds.		Mandatory	Accepted	IALA R-129 [4]
3.6	**Position Accuracy - Port Approach**	REQ-18	When the system is used for navigation in port approaches, restricted waters or inland waterways, the Horizontal Position Accuracy of the externally estimated position solution shall be at most 10 m, 95%.		Mandatory	Accepted	IALA R-129 [4]
3.7	**Integrity - Port Approach**	REQ-19	When the system is used for navigation in port approaches, restricted waters or inland waterways, the Integrity Risk of the externally estimated horizontal position shall be at most 1e-4 over a period of 3 hours, with a Horizontal Alert Limit (HAL) of 25		Mandatory	Accepted	IALA R-129 [4]

Key	Name	Identity	Requirement Details	Comments	Priority	Status	References
			m. Note: The continuity requirement (REQ-20) uses a time interval of 15 minutes. For compatibility reasons, it would be beneficial to use the same time interval for both the integrity and continuity requirements.				
3.8	**Time to Alarm - Port Approach**	REQ-25	The Base Station Health information shall be provided in such a manner that mariners using the system for navigation in port approaches, restricted waters and inland waterways can be warned of a system fault within 10 seconds of the fault occurring.		Mandatory	Accepted	IALA R-129 [4]
3.9	**Continuity - Port Approach**	REQ-20	When the system is used for navigation in port approaches, restricted waters or inland waterways, the Continuity of the externally estimated horizontal position solution shall be at least 99.97% over a time interval of 15 minutes.		Mandatory	Accepted	IALA R-129 [4]
3.10	**Fix Interval - Port Approach**	REQ-21	When used for navigation in port approaches, restricted waters or inland waterways, the system shall provide new observables to the external processor at least once every 2 seconds.		Mandatory	Accepted	IALA R-129 [4]
4	**Capacity - Goal**	REQ-22	The system should, as a goal, be capable of being used by an unlimited number of ships. Capacity may be limited if using active ranging.		High	Accepted	IMO Resolution A.1046(27) [5] R-Mode Baltic - Baseline and Priorities (Draft) [2]
5	**Interface - Goal**	REQ-5	The system should use standardized and approved communication protocols for interfacing.		High	Accepted	IMO Resolution MSC.401(95) [1]
6	**Security**	REQ-6	The system shall be designed to consider cyber-attacks (including jamming and spoofing) so that such events can be detected and their effects mitigated.		Mandatory	Accepted	VDES R-Mode Requirements [6]
7	**Regulatory**	REQ-7				Accepted	

Key	Name	Identity	Requirement Details	Comments	Priority	Status	References
7.1	**ITU Radio Regulations**	REQ-23	The system shall be designed and operated in accordance with ITU Radio Regulations, Article 28.	This may mean that additional (radiodetermination service) allocations will need to be made for the VDES frequencies under Radio Regulations Chapter II, Article 5 and a designation under Appendix 18.	Mandatory	Accepted	ITU Radio Regulations [7]
8	**Environmental**	REQ-27				Accepted	
8.1	**GNSS Disruption at Ship**	REQ-26	Following a disruption to GNSS services (due to jamming/spoofing/interference/satellite failures, etc.) local to the ship, the system shall continue to meet the Functional, Coverage and Performance Requirements set out in this specification for an unlimited period of time. For the purpose of this requirement, it is assumed that GNSS reception at the locations of the VDES R-Mode Base Station Infrastructure is nominal.		Mandatory	Accepted	
8.2	**GNSS Disruption at Infrastructure**	REQ-28	Following a disruption to GNSS services (due to jamming/spoofing/interference/satellite failures, etc.) at one or more locations of the VDES R-Mode Base Station Infrastructure, and regardless of GNSS service availability and performance at the ship's location, the system shall continue to meet the Functional, Coverage and Performance Requirements set out in this specification for a minimum duration of 2 hours.	This means the BS will need to be able to detect GNSS disruptions.	Mandatory	Accepted	R-Mode Baltic - Baseline and Priorities (Draft) [2]
8.3	**GNSS Disruption at Infrastructure - Goal**	REQ-29	Following a disruption to GNSS services (due to jamming/spoofing/interference/satellite failures, etc.) at one or more locations of the VDES R-Mode Base Station Infrastructure, and regardless of GNSS service availability and performance at the ship's location, the system should, as a goal, continue to meet the Functional, Coverage and Performance Requirements set out in this specification for an unlimited period of time.		Medium	Accepted	VDES R-Mode System Requirements [3]

Key	Name	Identity	Requirement Details	Comments	Priority	Status	References
8.4	**Ship Dynamics**	REQ-32	The system shall meet the requirements set out in this specification during static and dynamic ship operations.	One critical issue with this respect is the measurement update rate.	Mandatory	Accepted	IMO Resolution MSC.401(95) [1]
9	**Resource**	REQ-33				Accepted	
9.1	**VDES Channels**	REQ-35	The system should operate on the VDE-TER or ASM channels.	It is acknowledged that VDE will provide better performance than AIS R-Mode but implementing R-Mode using AIS could be a start.	Medium	Accepted	VDES R-Mode Development and Standardisation [8]
9.2	**VHF Data Link Loading - Goal**	REQ-34	The system should impose a maximum additional VDES Data Link loading of 7% of the total link capacity.	7% may not be sufficient due to slot use coordination requirements. The coordination distance between two AIS BS is probably 120 NM.	High	Accepted	VDES R-Mode Development and Standardisation [17]
10	**Testability**	REQ-36				Accepted	
10.1	**Self-testability**	REQ-37	The system shall be designed to support self-testability.		High	Accepted	R-Mode Baltic - Baseline and Priorities (Draft) [2]
10.2	**Remote Monitoring**	REQ-38	The system shall be designed to support remote infrastructure monitoring.		High	Accepted	R-Mode Baltic - Baseline and Priorities (Draft) [2]
11	**Interoperability**	REQ-40	The system shall be interoperable with Medium Frequency R-Mode, eLoran and other similar PNT systems.	If possible, using the same time base, geodetical coordinate systems, etc.	Mandatory	Accepted	R-Mode Baltic - Baseline and Priorities (Draft) [2]